Electrons on the brink of localization:
Heavy fermions and the d-f connection

Piers Coleman
Center for Materials Theory
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- Introduction - the **d-f** connection, heavy fermion primer.

A new era of mysteries:

- Quantum Criticality
- Spin in (heavy fermion) superconductivity
- Hidden order in URu2Si2
- Vortex model for intrinsically quantum critical YbAlB4.

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Notes:

"Many Body Physics: an introduction", Ch 8,15-16", PC, CUP to be published (2011). http://www.physics.rutgers.edu/~coleman.

"Heavy Fermions: electrons at the edge of magnetism." Wiley encyclopedia of magnetism. PC. cond-mat/0612006.

"Wurzburg Lectures on Heavy Fermion Physics", http://harpsichord.rutgers.edu/~coleman/talks/wurzburg2011.pdf

General reading:

A. Hewson, "Kondo effect to heavy fermions", CUP, (1993).

"The Theory of Quantum Liquids", Nozieres and Pines (Perseus 1999).

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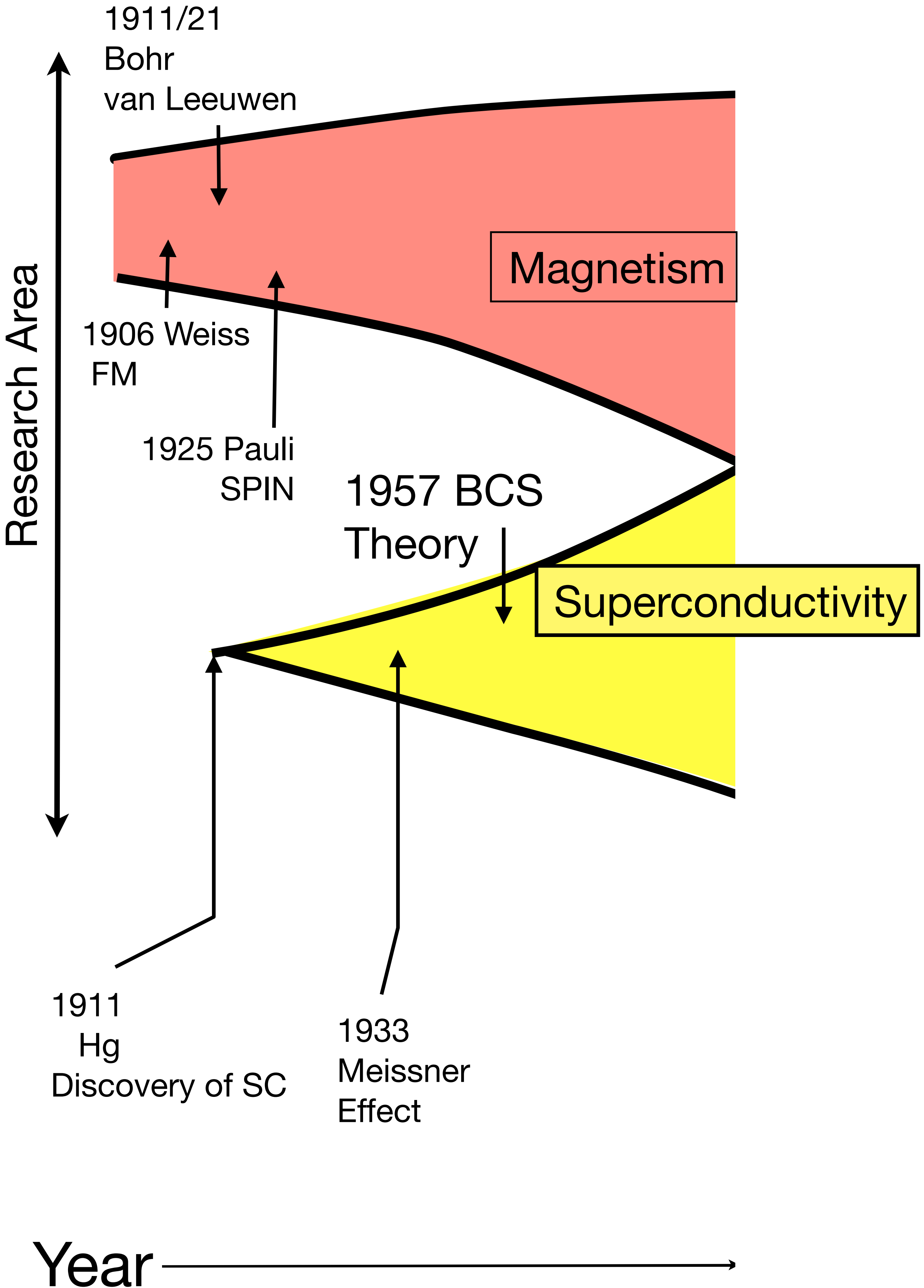
The d-f connection.

Magnetism and Superconductivity (After K. Miyake)



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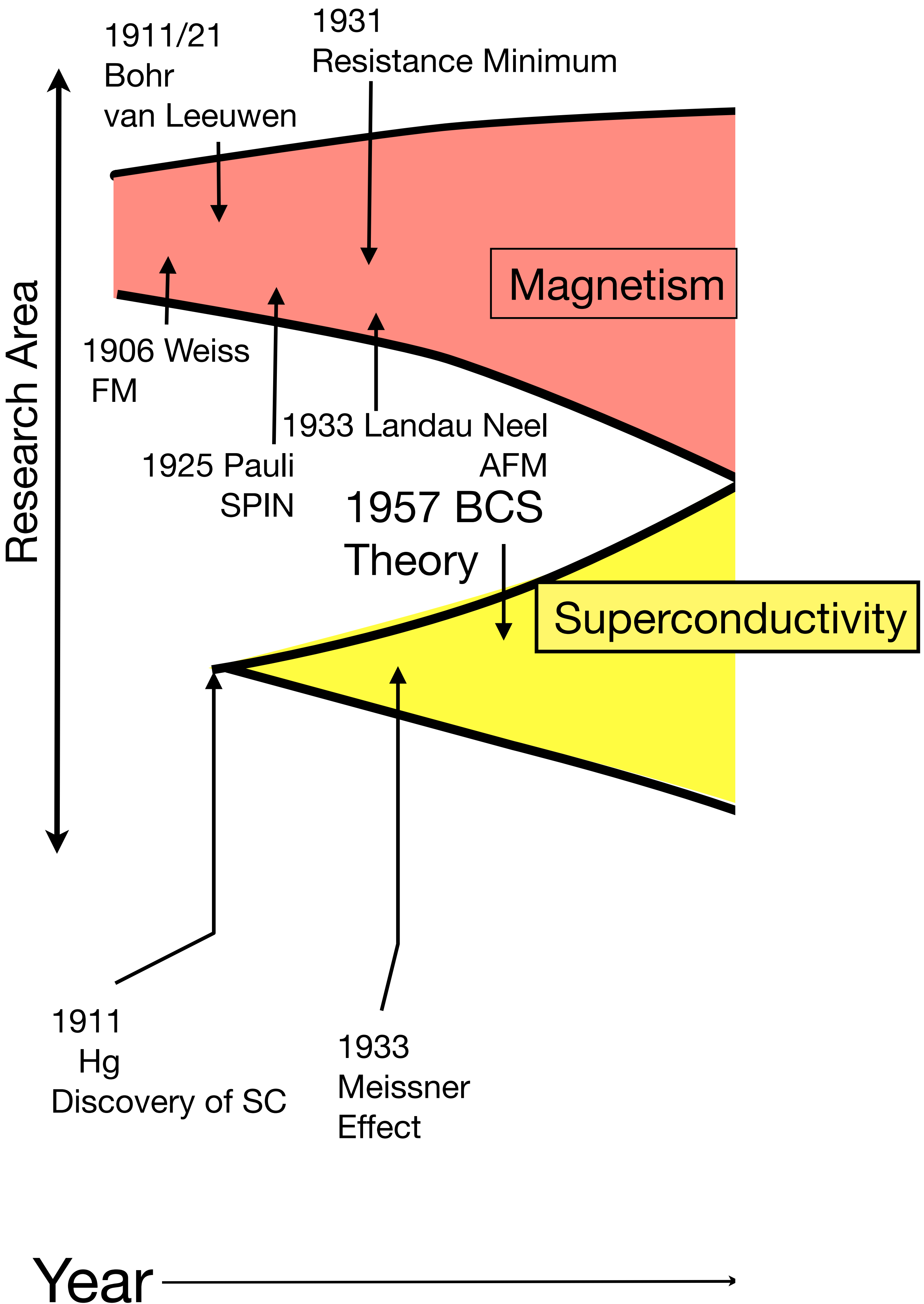

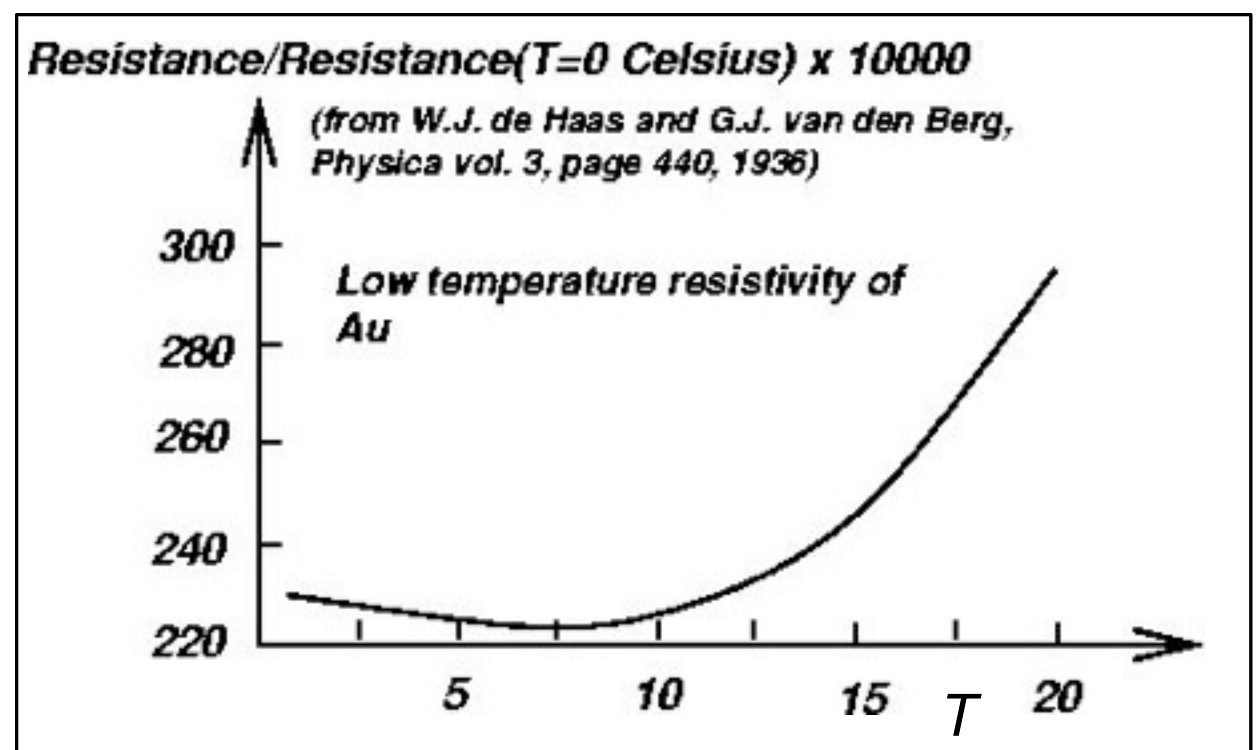

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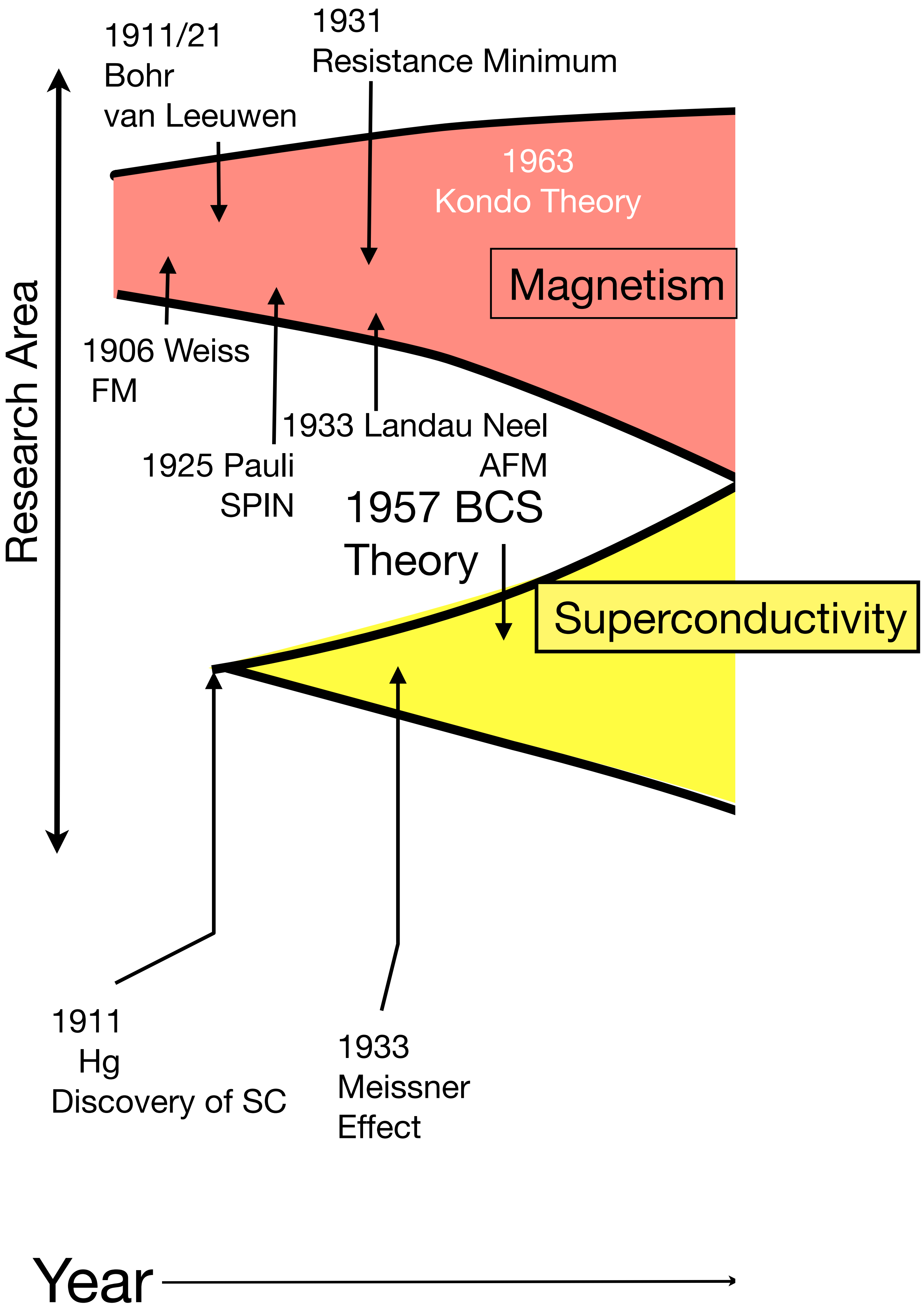
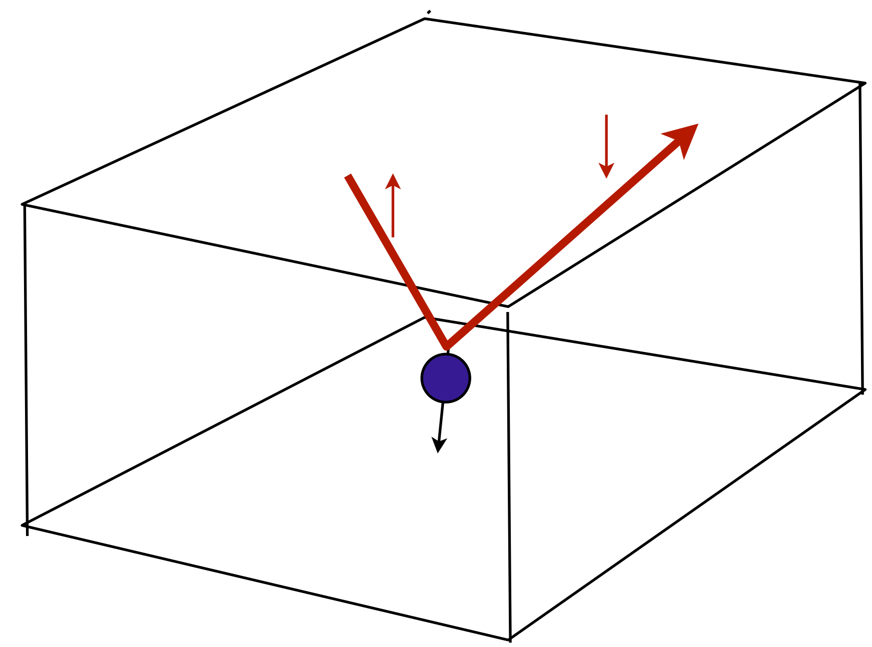
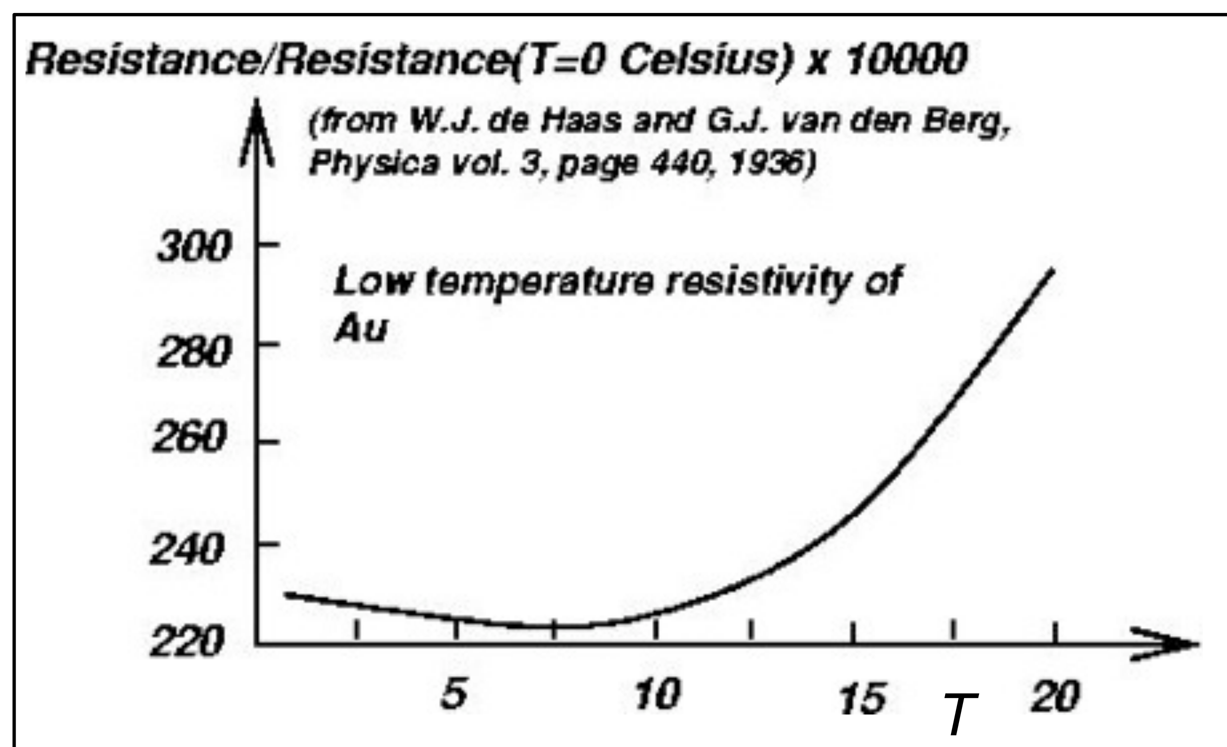


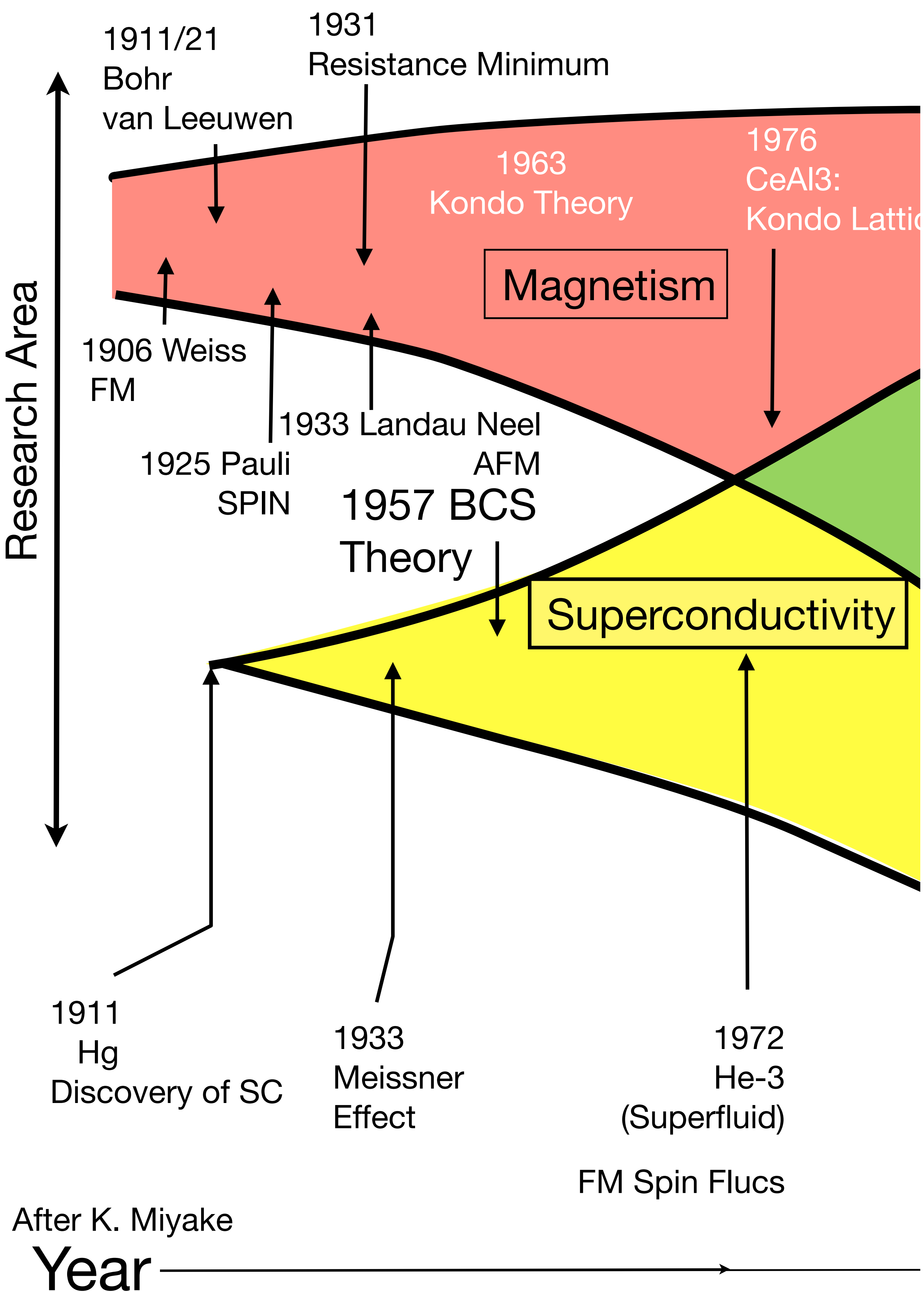


Kondo, 1963

$$J\rho \to J\rho + 2(J\rho)^2 \ln(D/T) + \ldots$$



A remarkable convergence of two fields.



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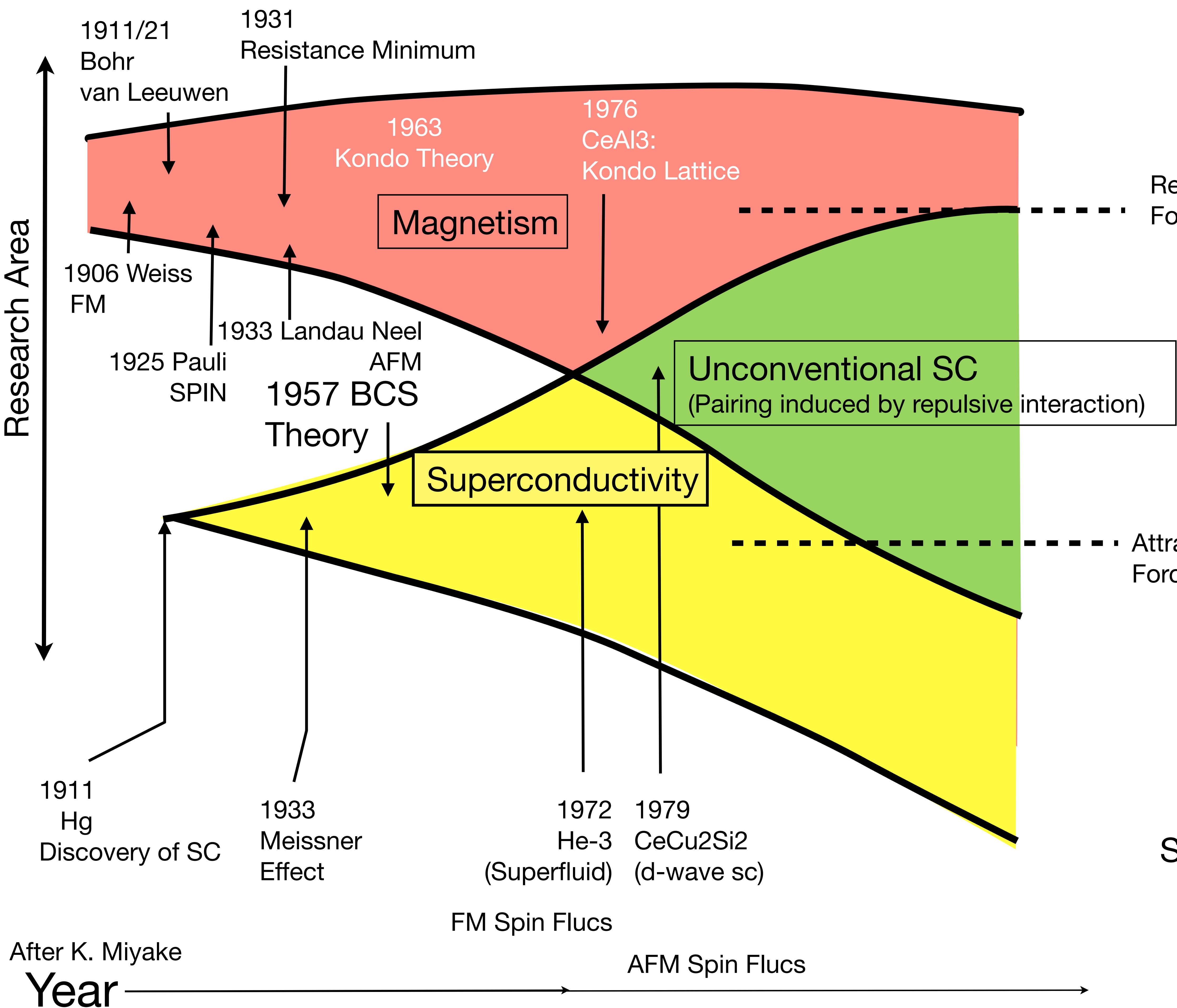

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Steglich, 1979

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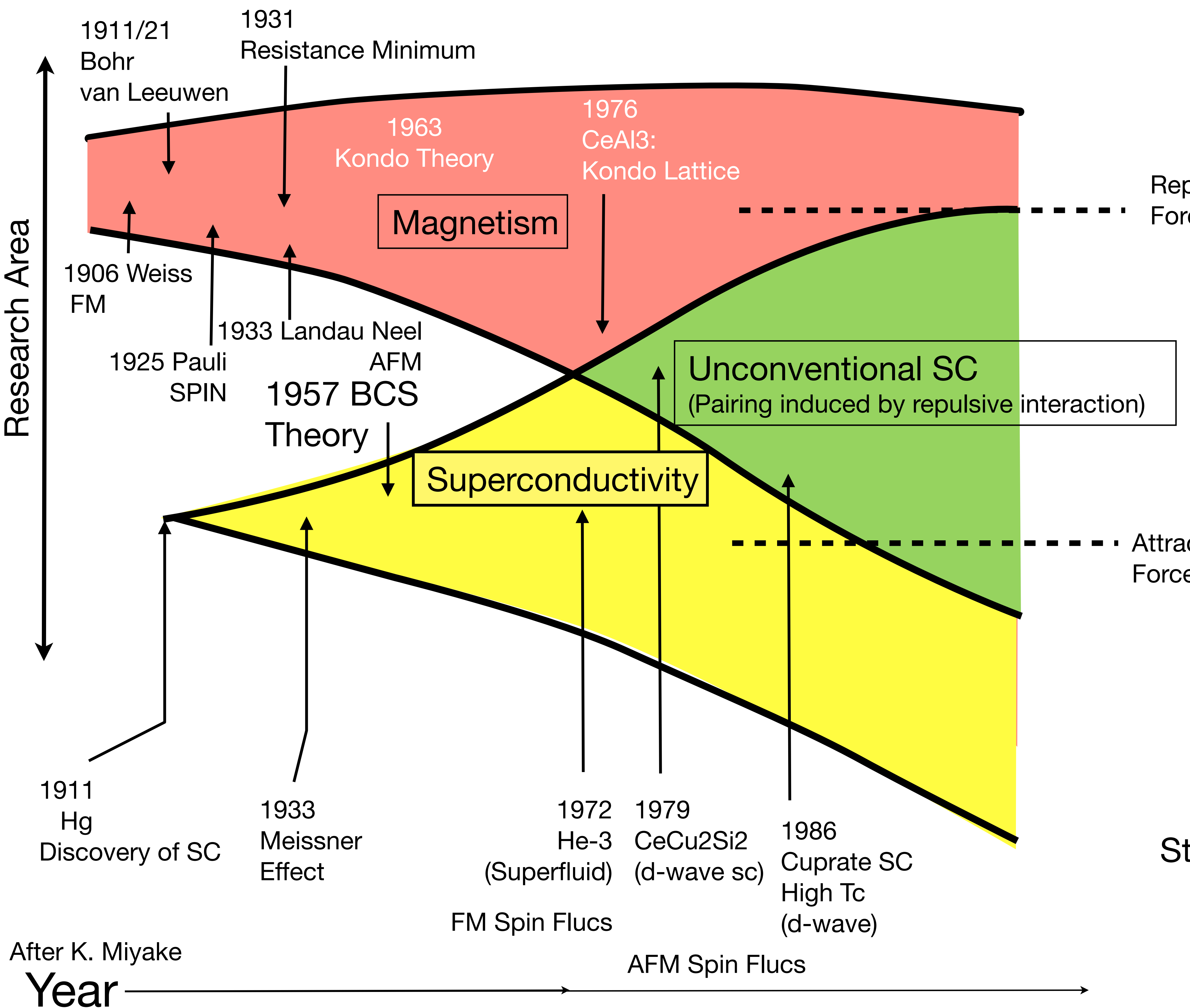


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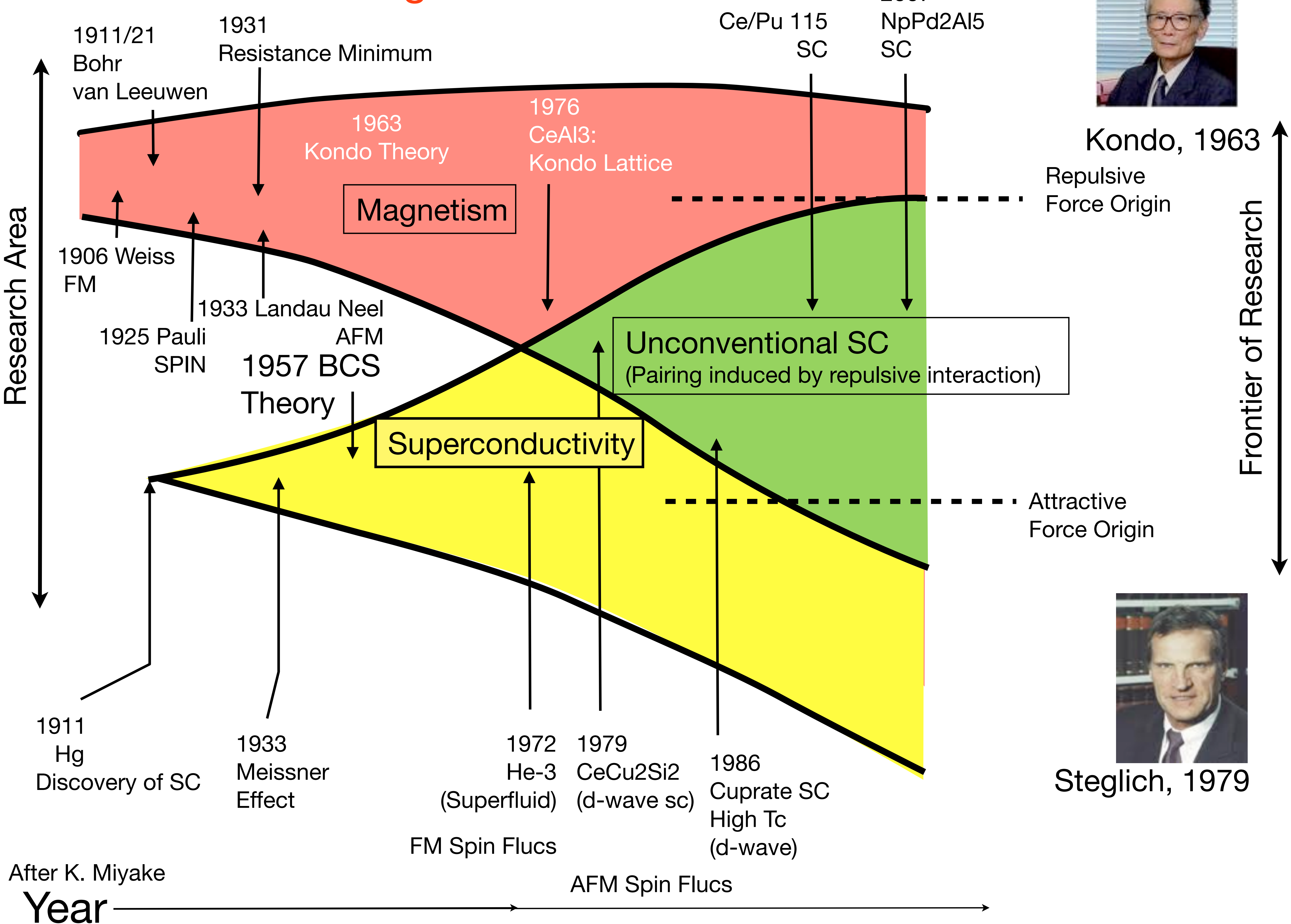

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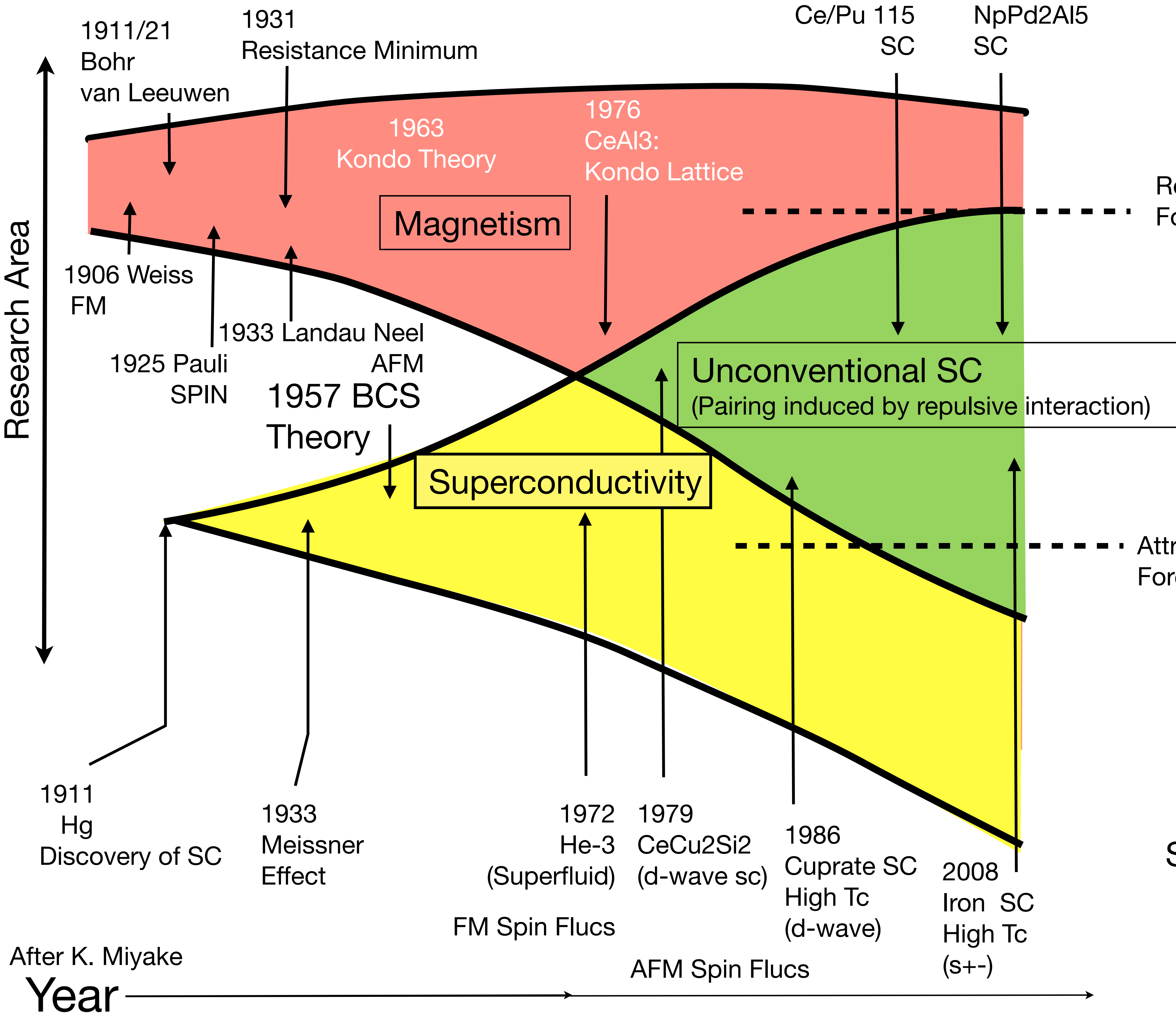


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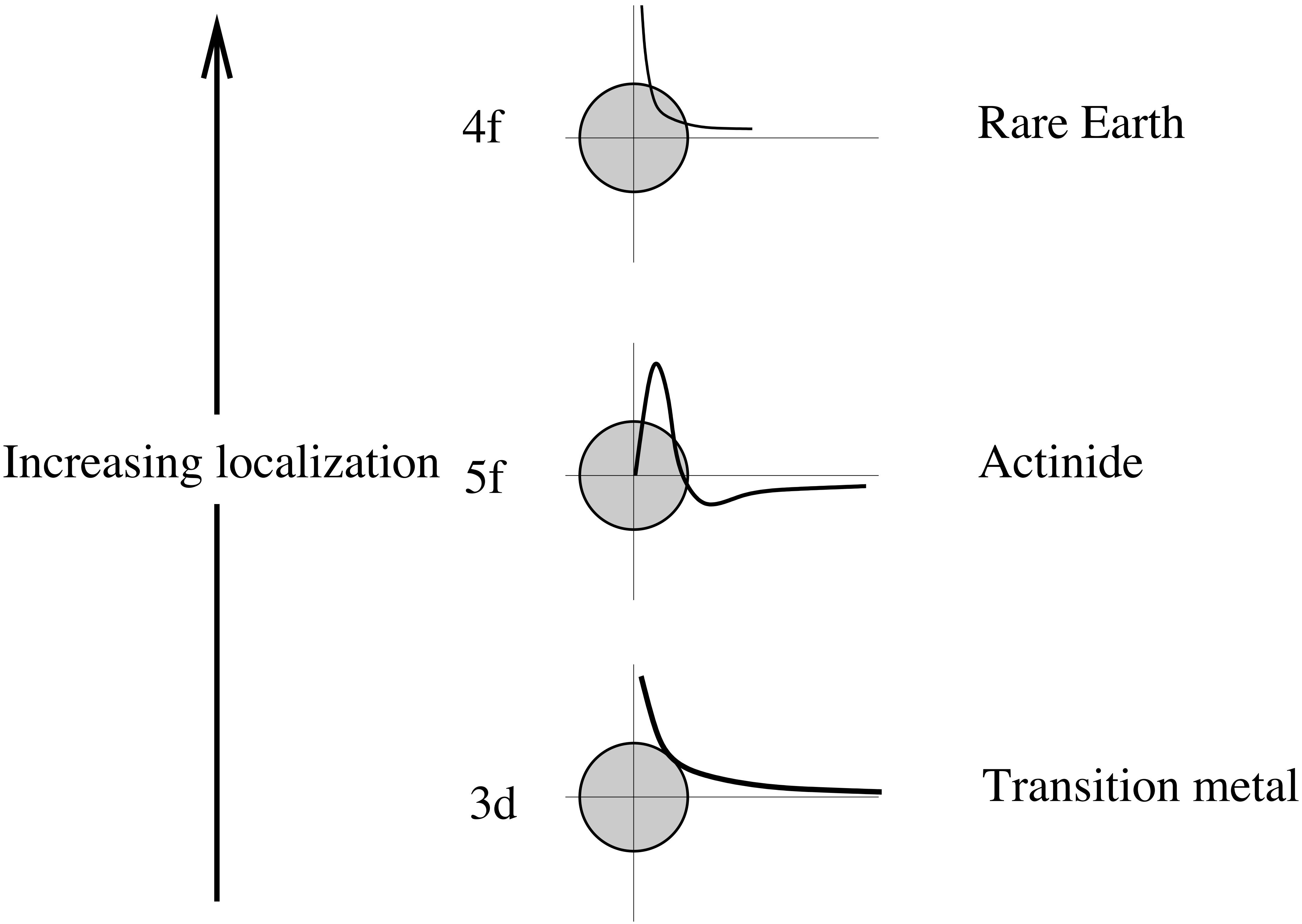
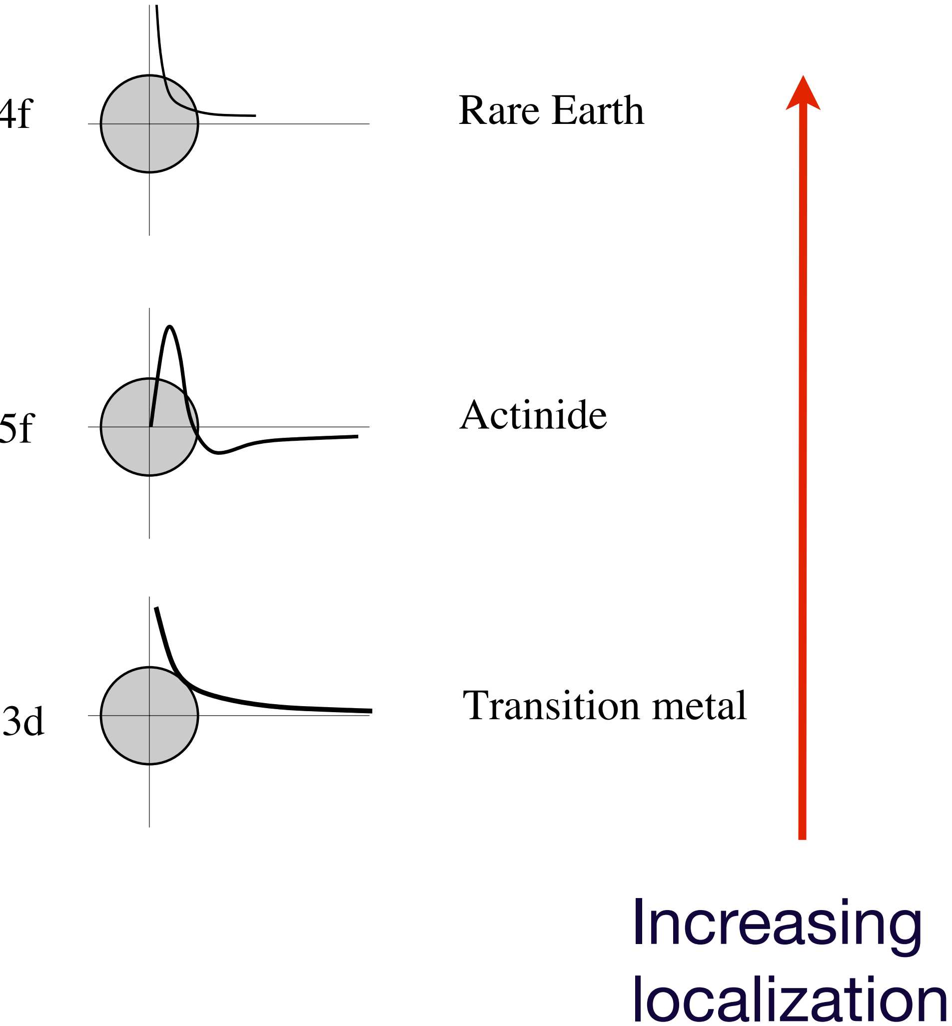

Increasing localization
4f
Rare Earth
5f
Actinide
3d
Transition metal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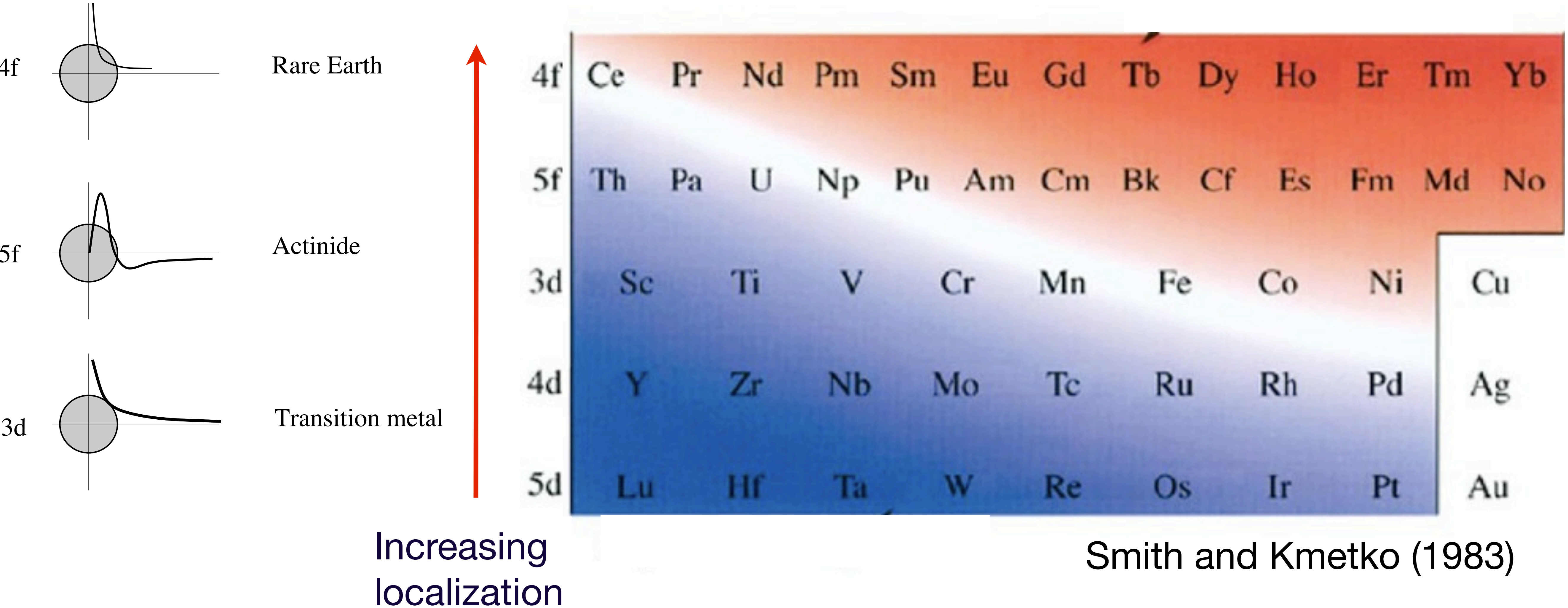
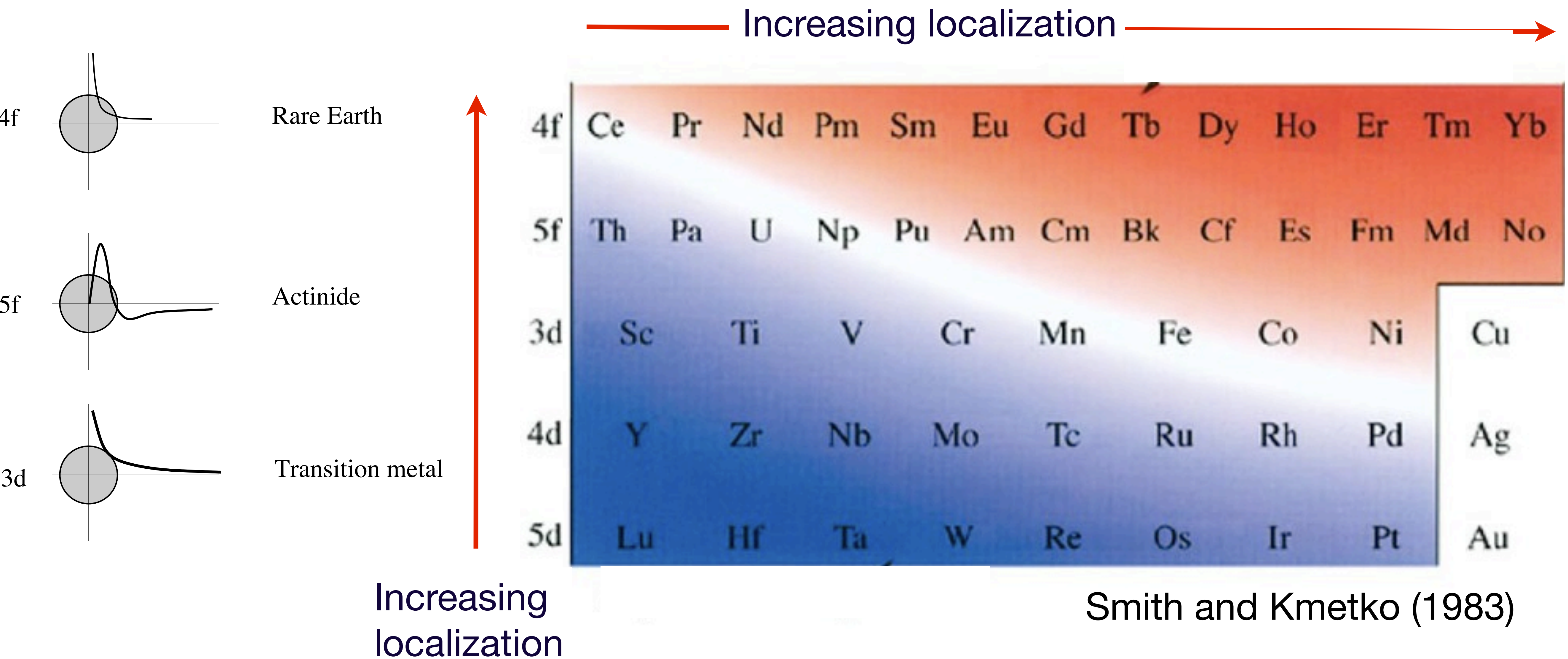


Smith and Kmetko (1983)



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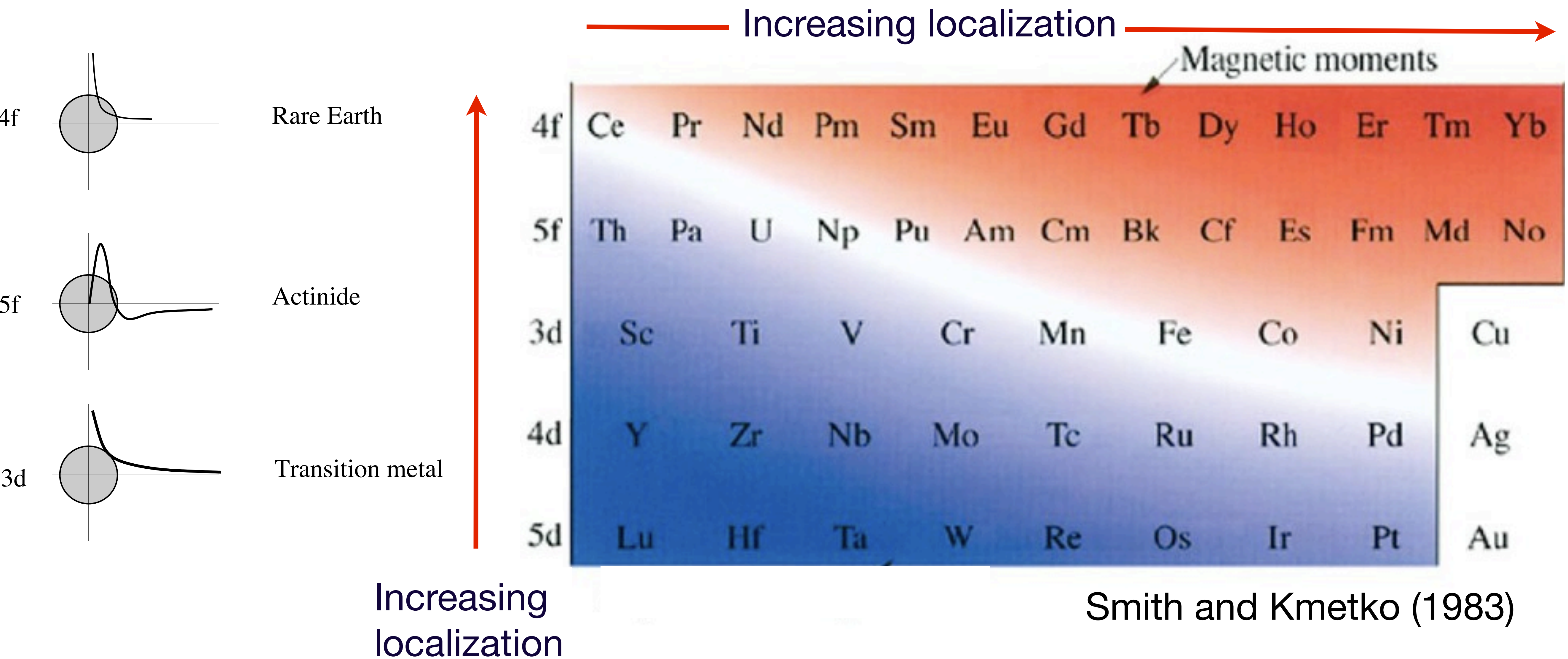

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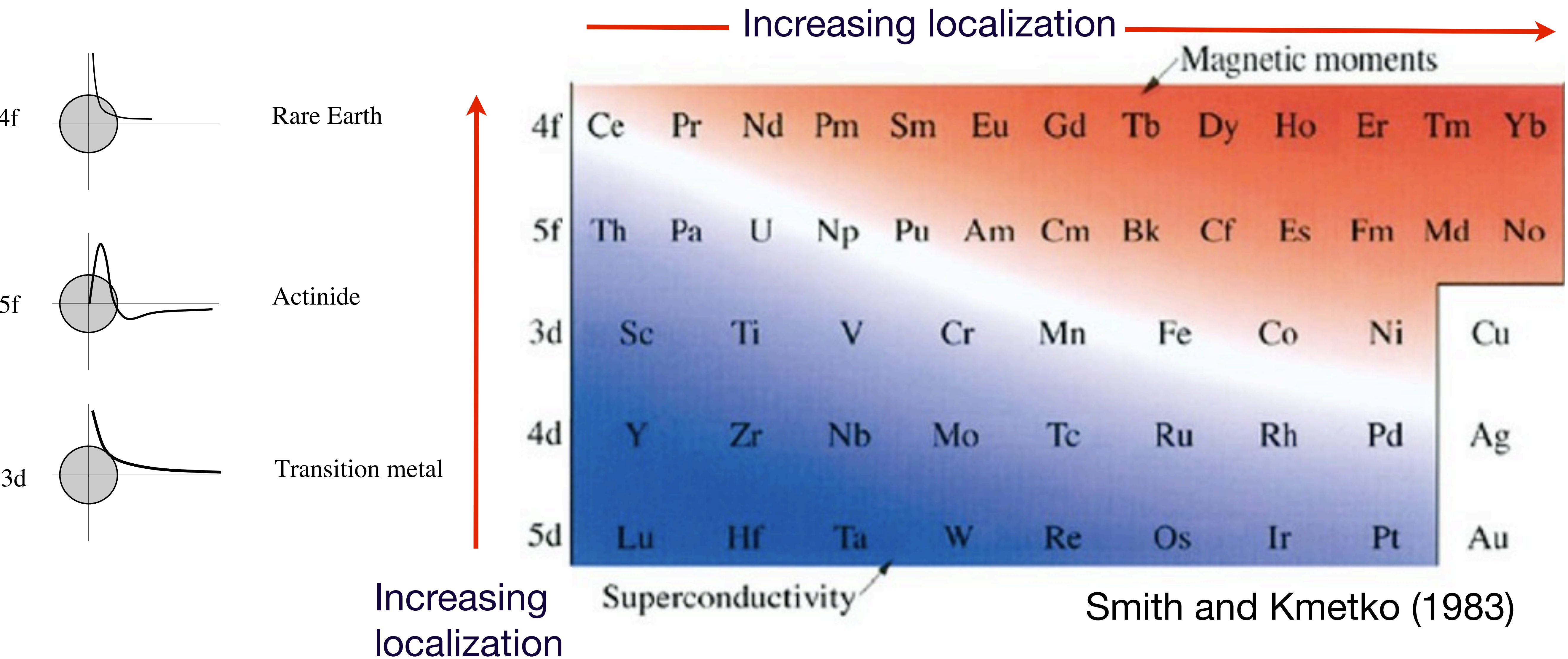

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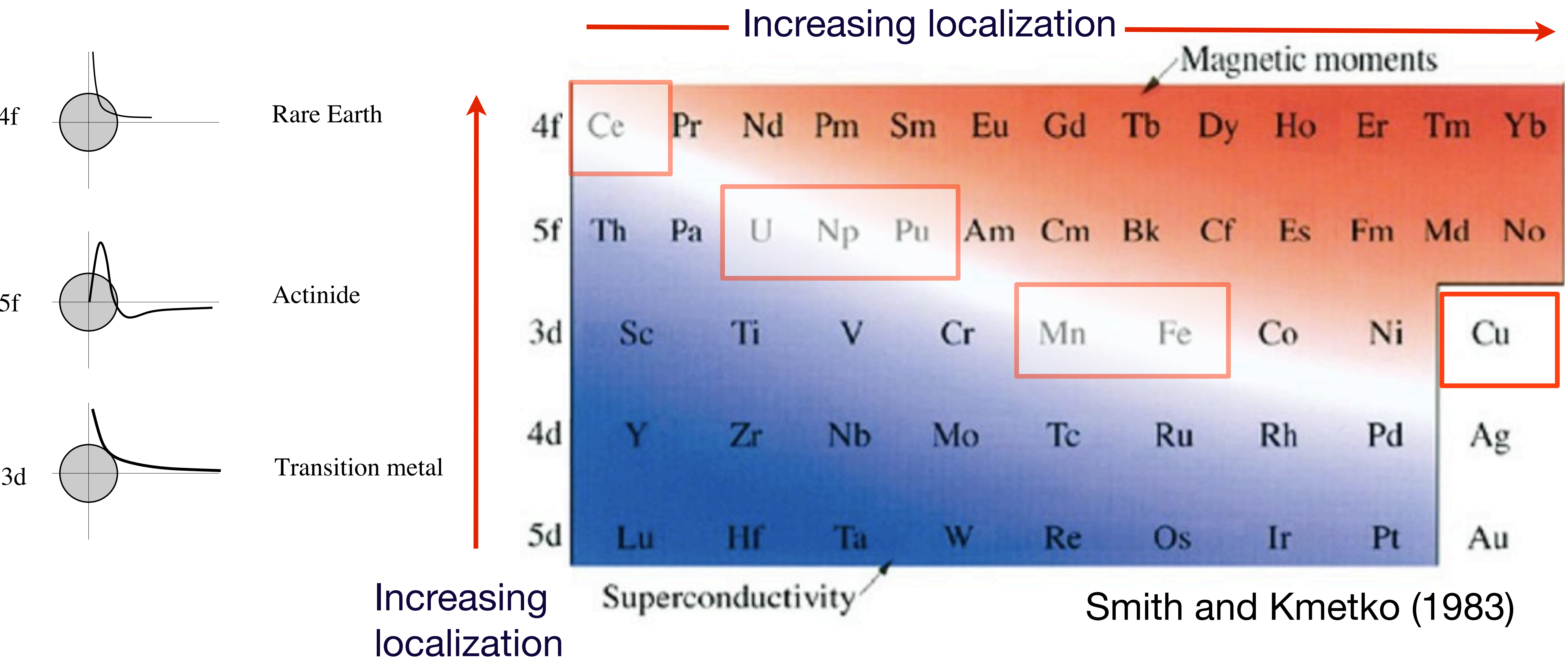

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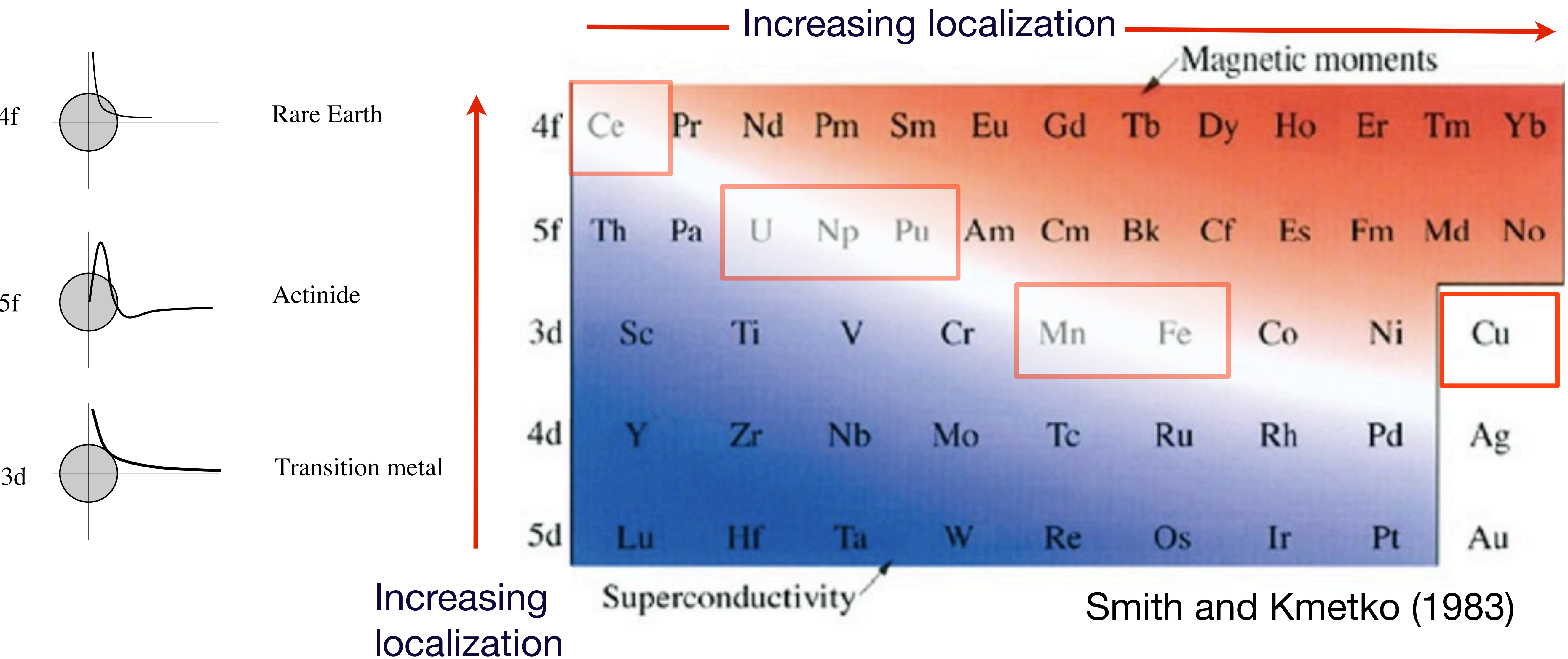

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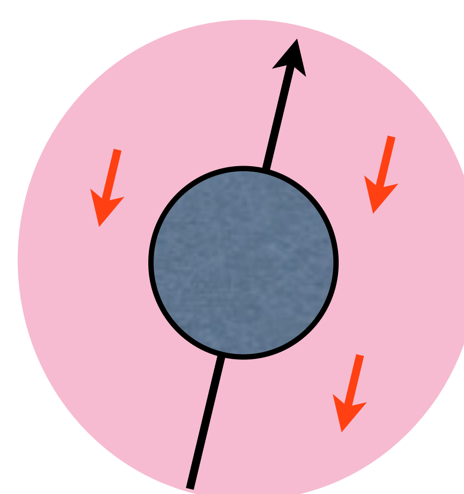
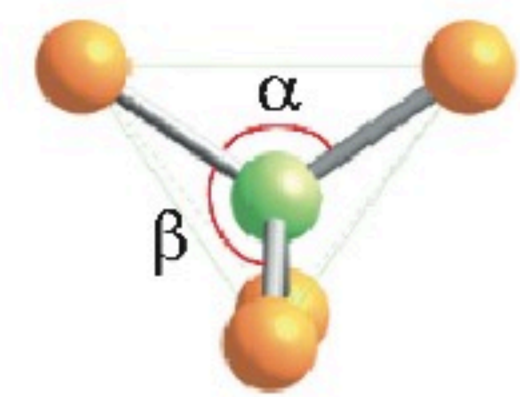
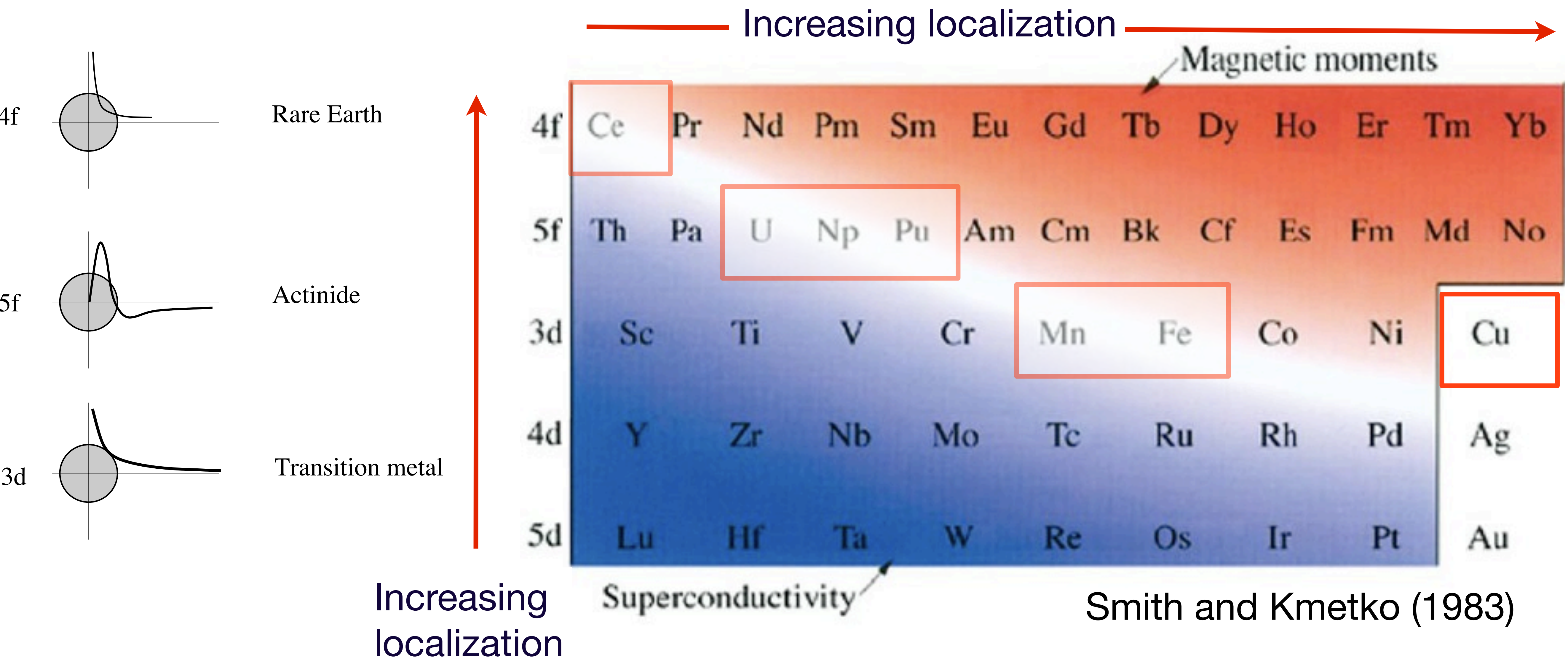


Ce^{3+} ion



$FeAs_4$-tetrahedron



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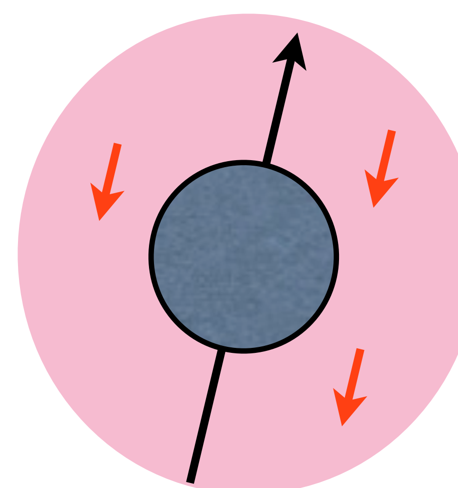
Localized degrees of freedom drive the emergent physics in f and d electron materials.



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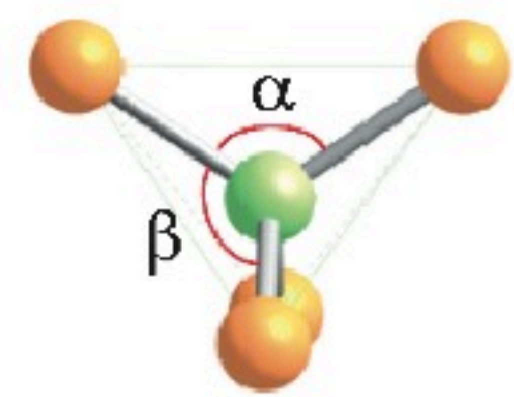

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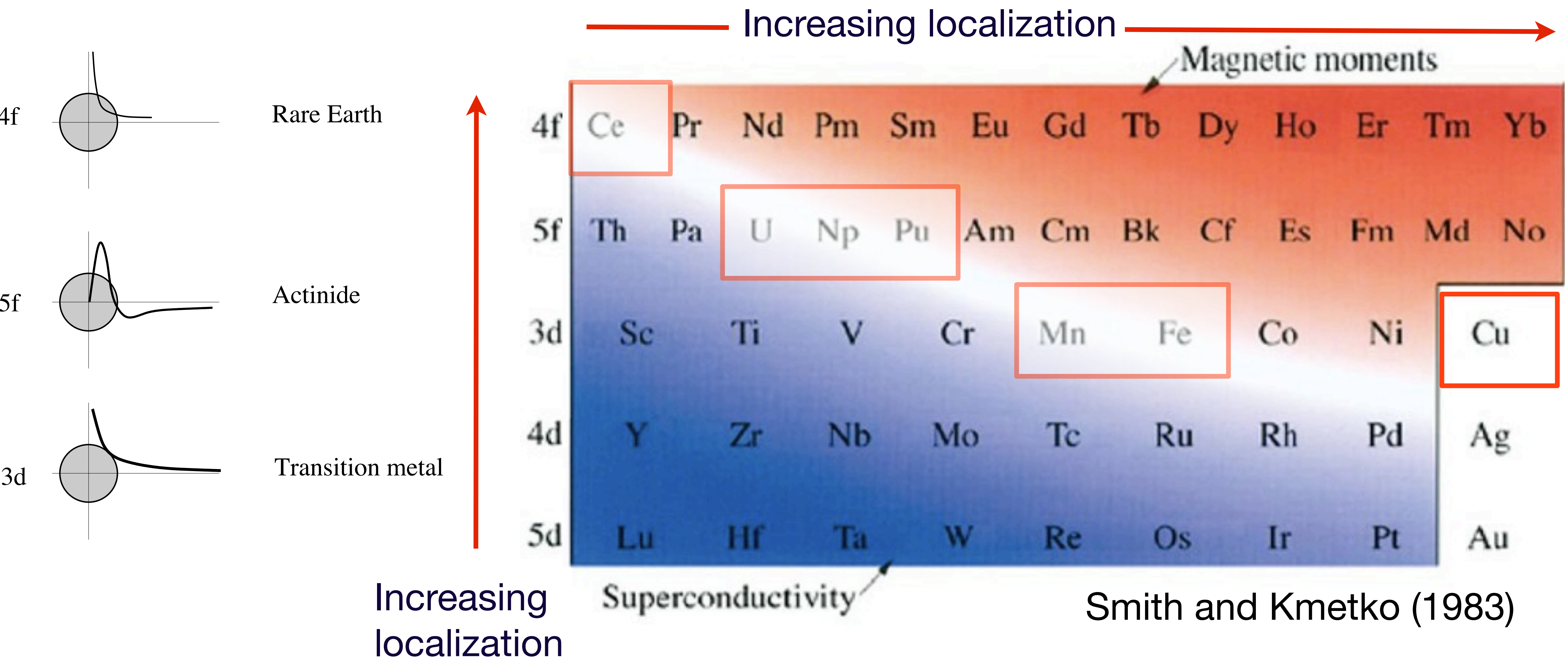

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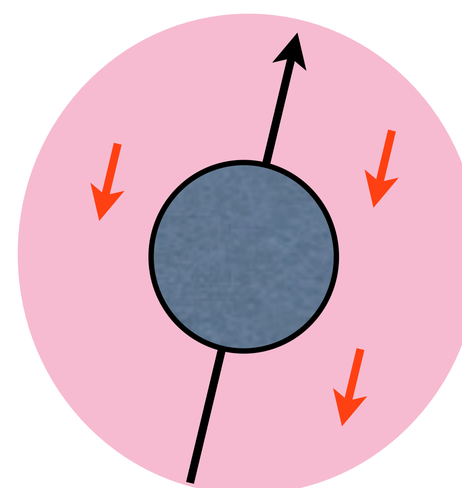

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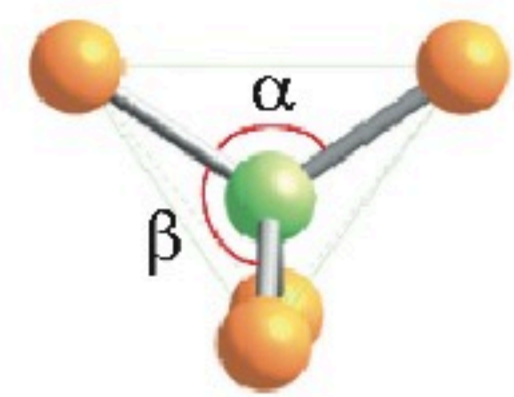
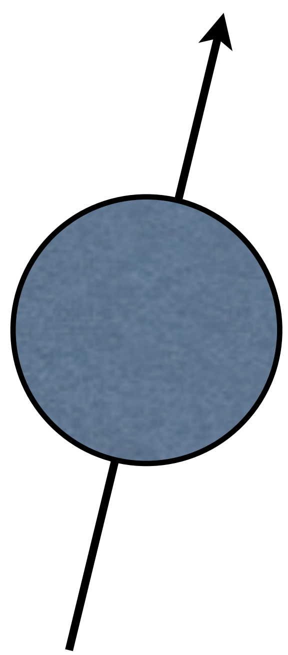


$FeAs_4$-tetrahedron

The d-f connection provides an unprecedented opportunity to develop a unified understanding of the frontier of magnetism, superconductivity and novel quantum materials. f-electrons, with their diversity and tunability, offer many experimental and theoretical advantages for research.

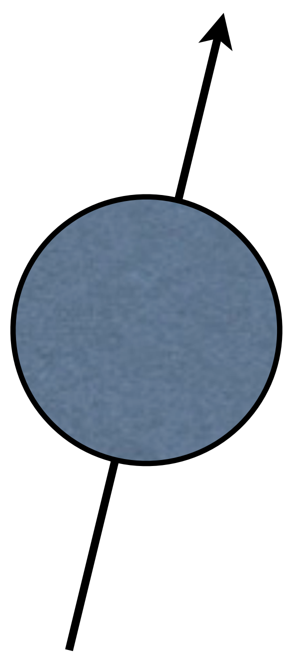
Heavy Fermion Primer.

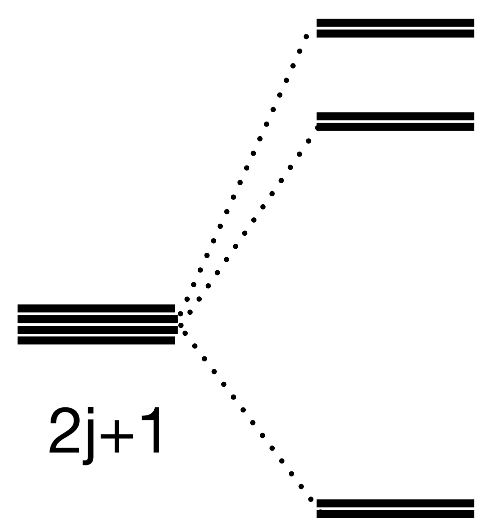
Heavy Fermion Primer



Spin: basic fabric
of heavy electron
physics.

Heavy Fermion Primer





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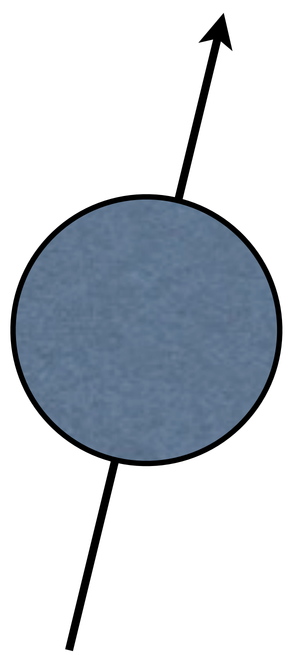

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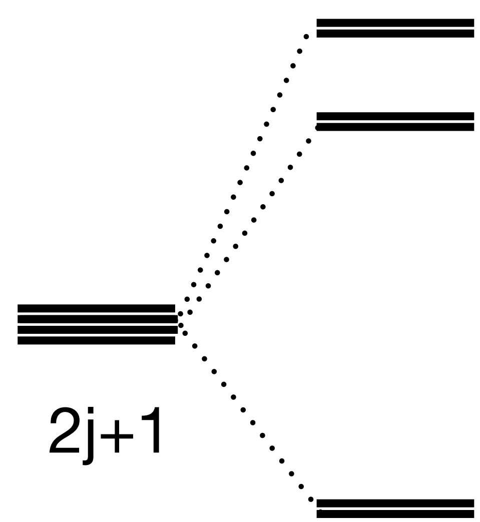

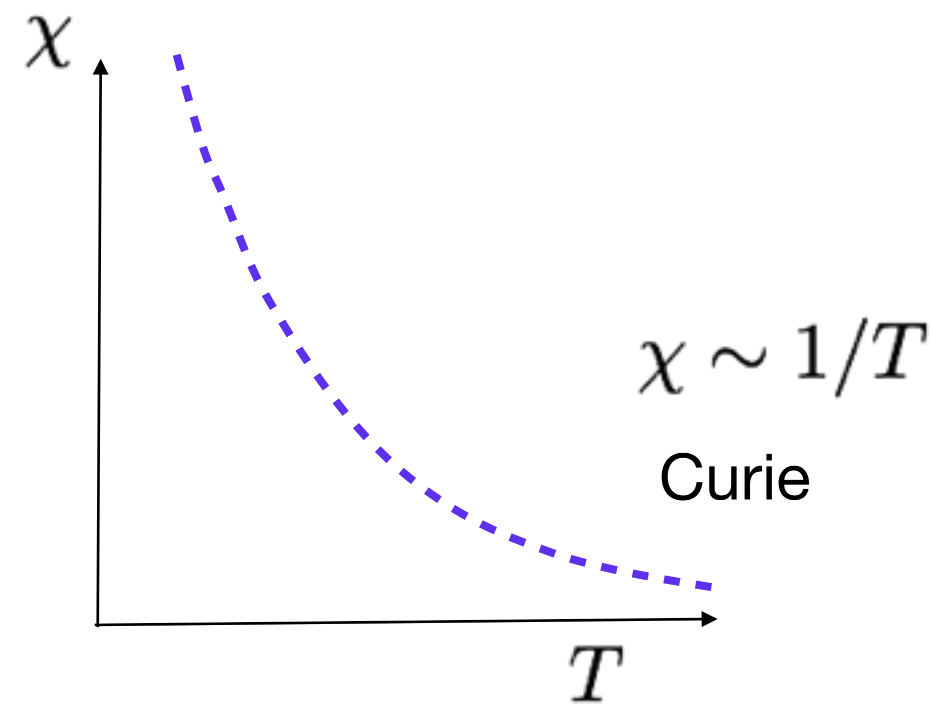

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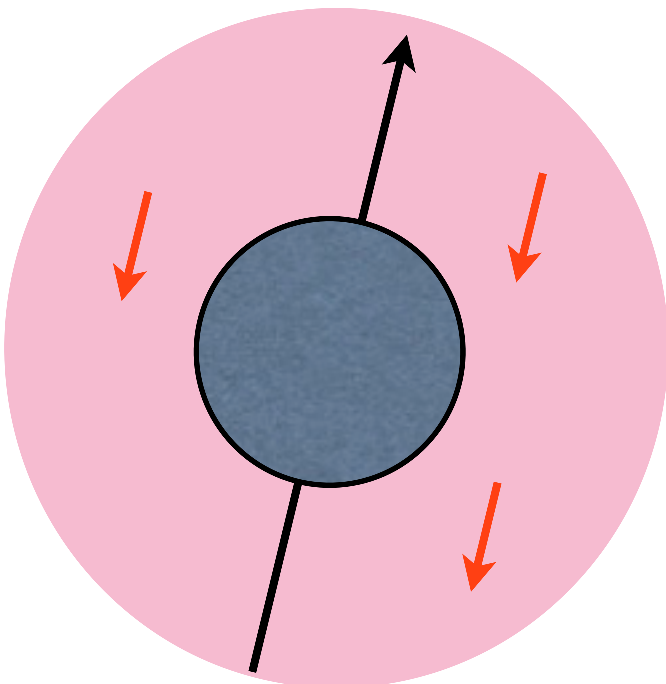
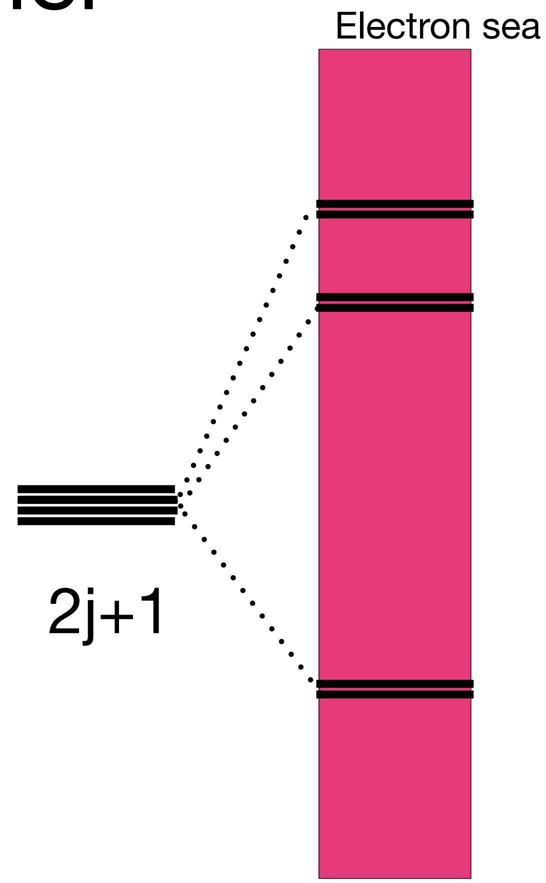
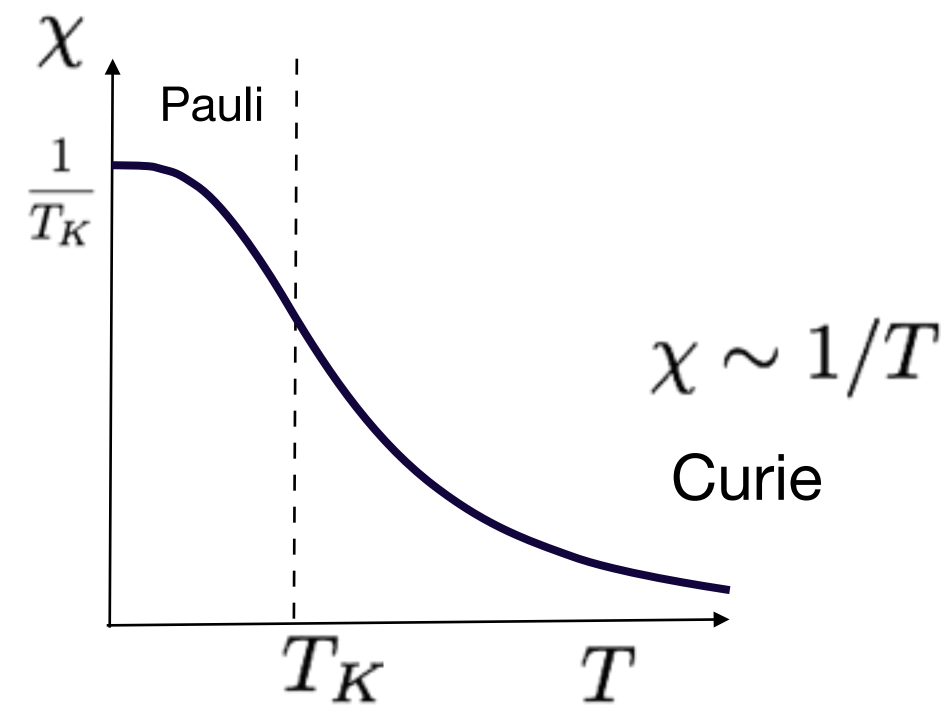


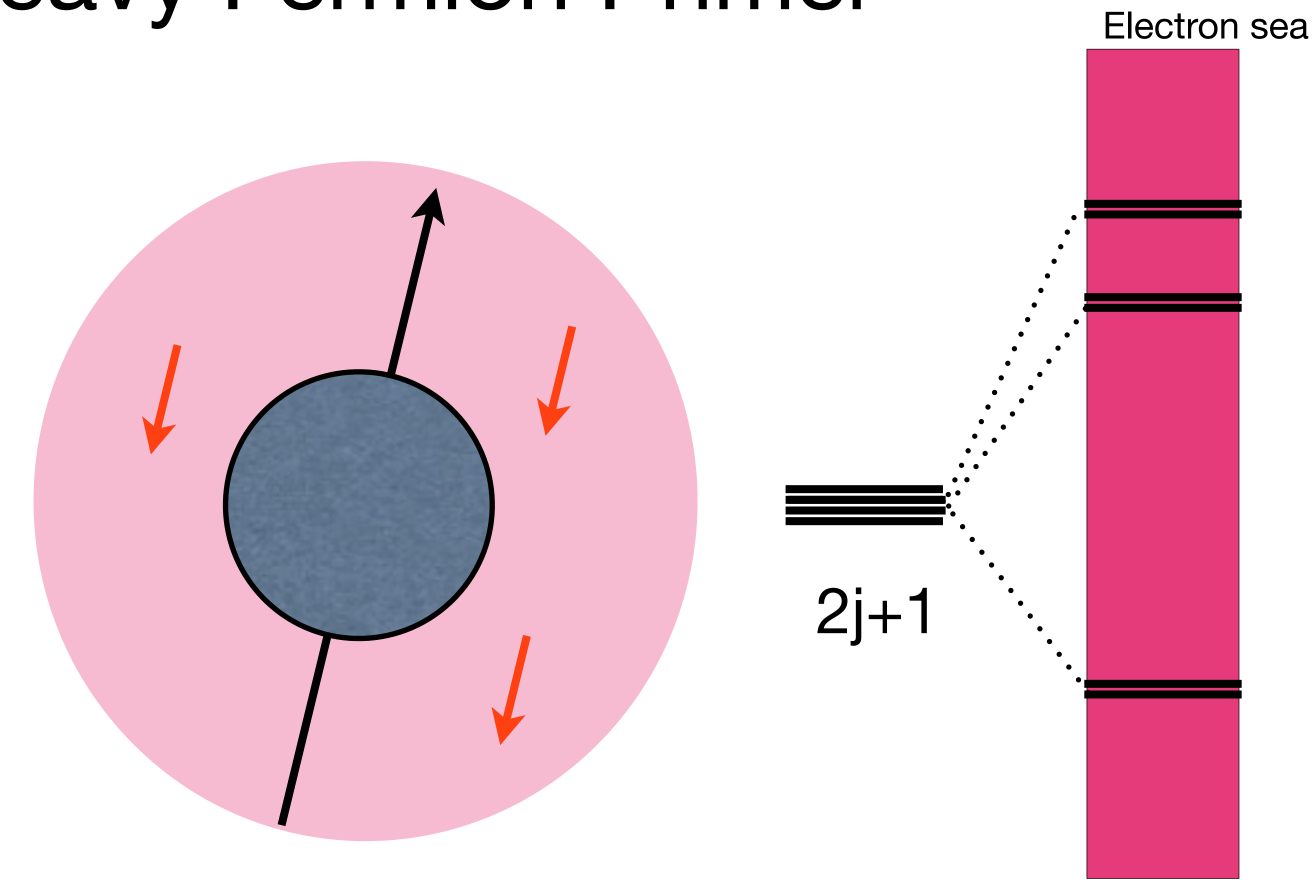
Spin screened by
conduction
electrons





"Kondo temperature"

Heavy Fermion Primer



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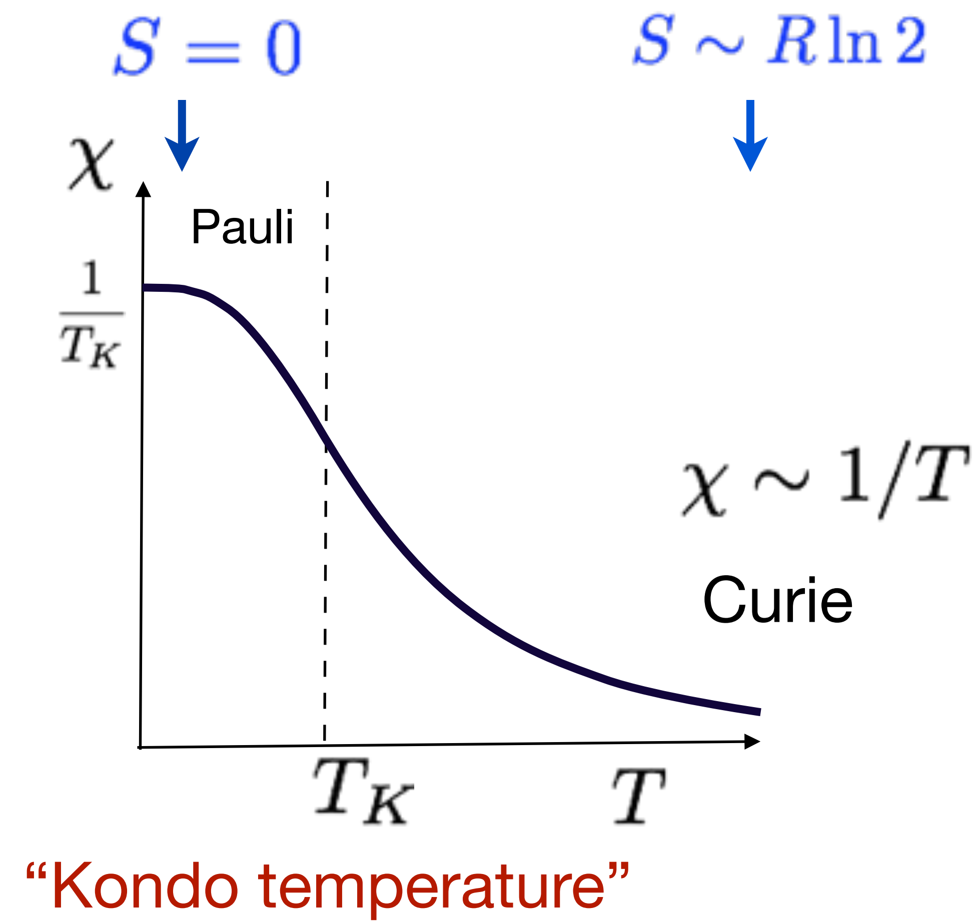

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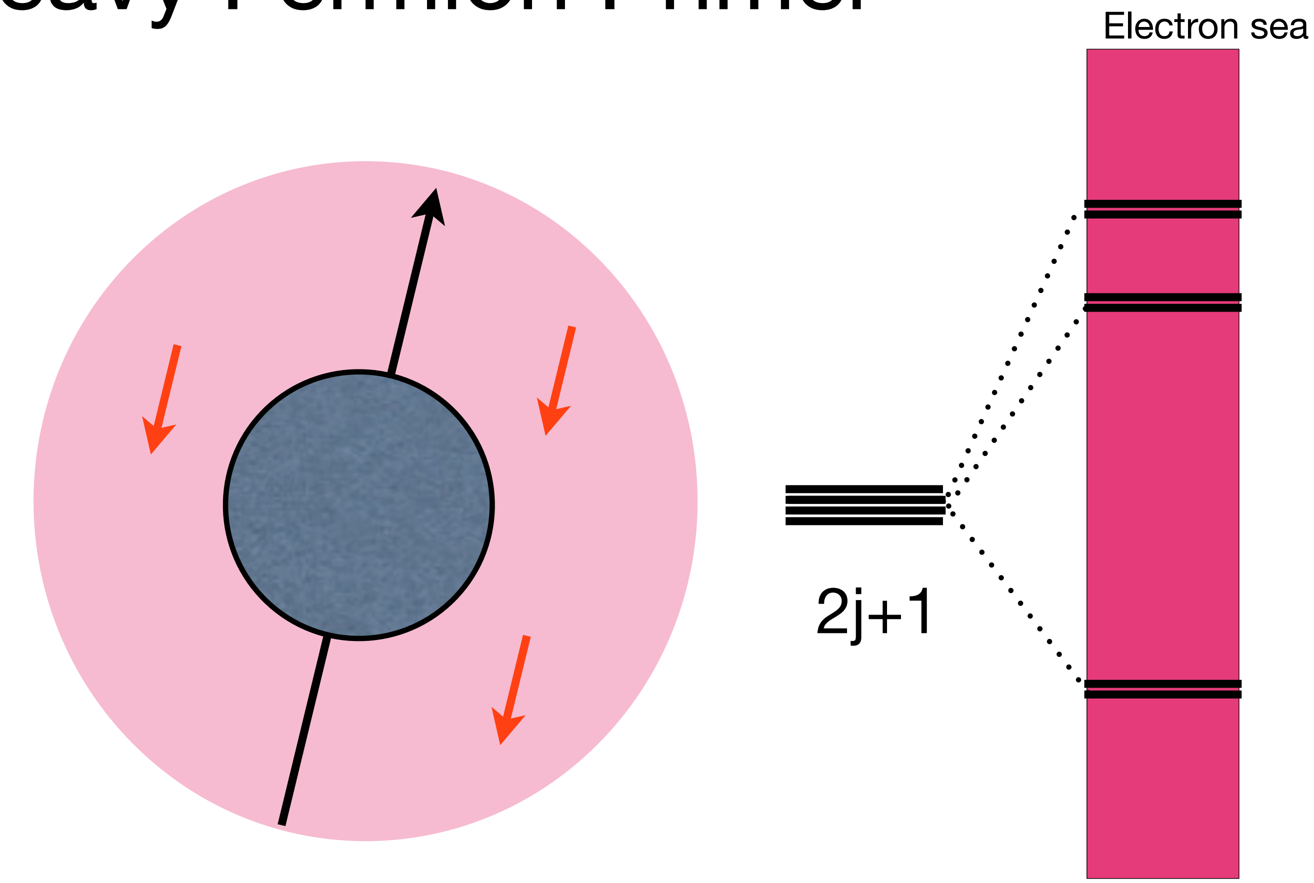

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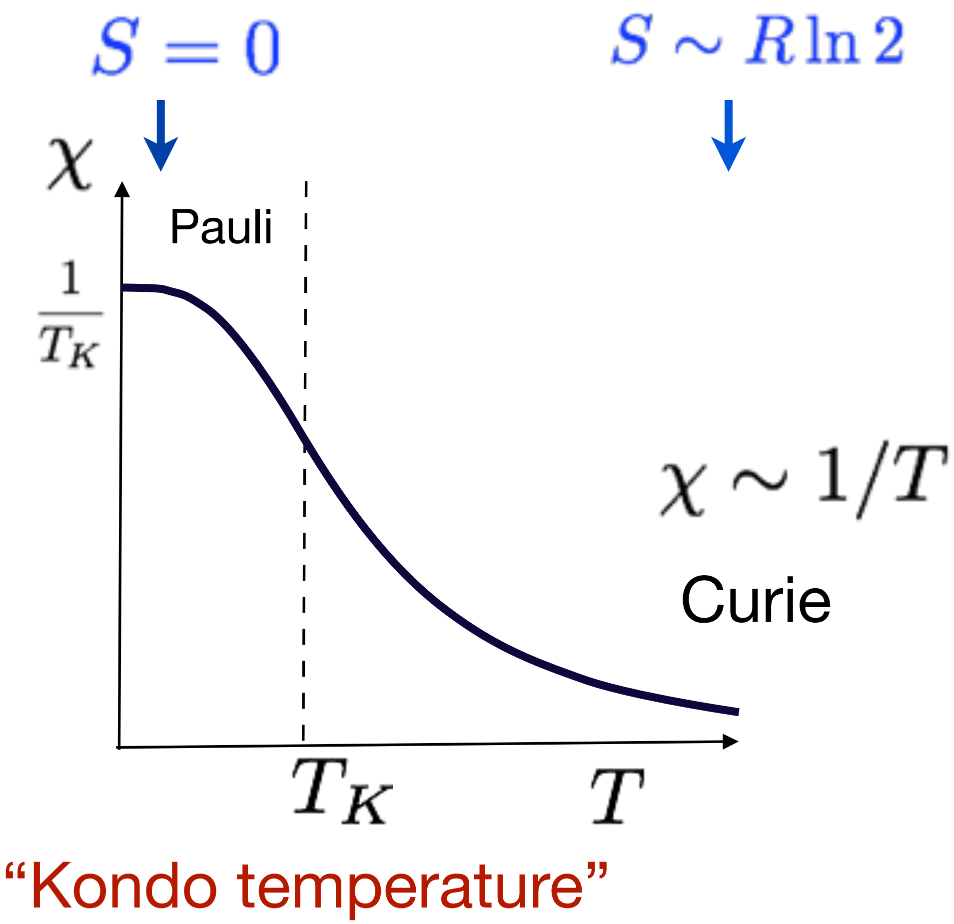
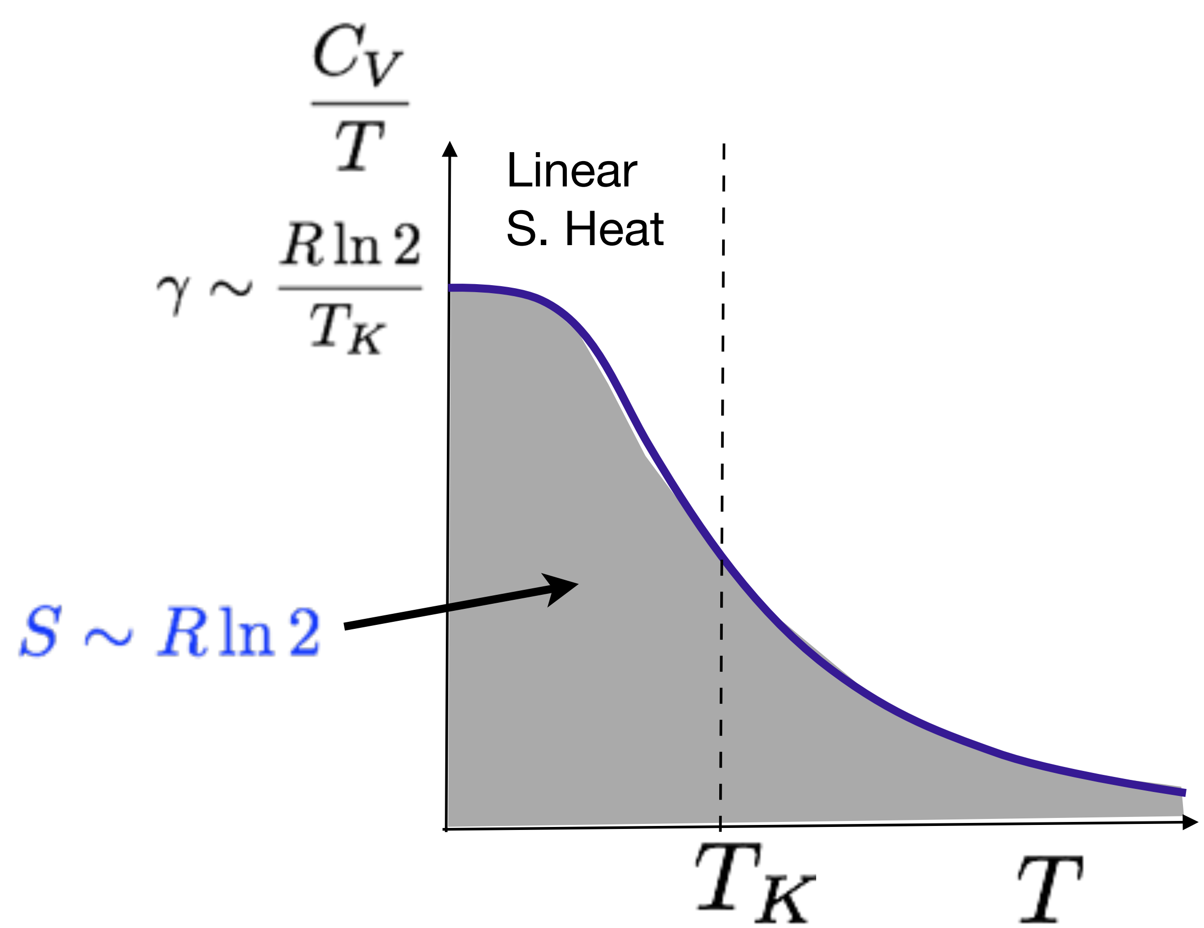
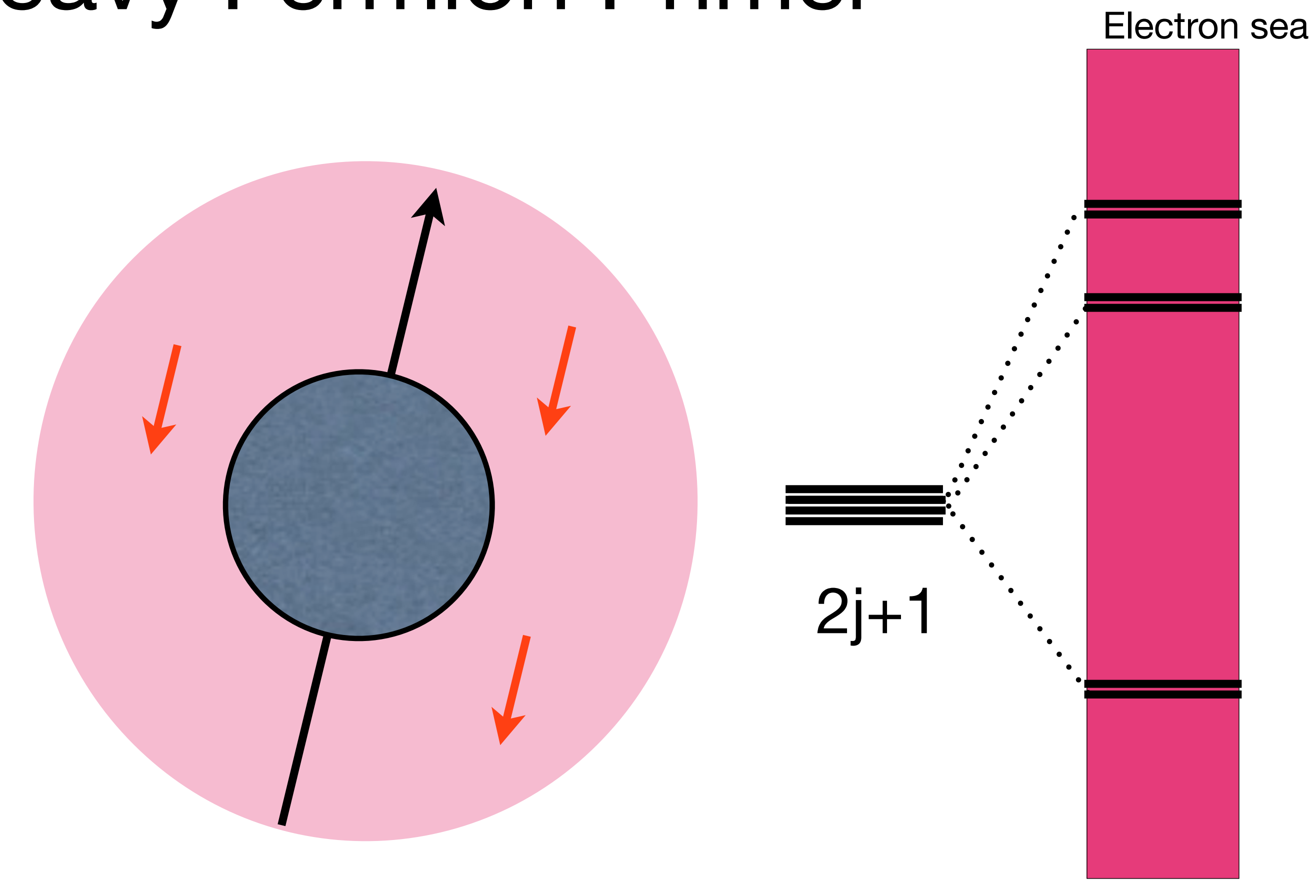




$$S(T) = \int_0^T \frac{C_V}{T'} dT'$$

Spin entropy

Heavy Fermion Primer



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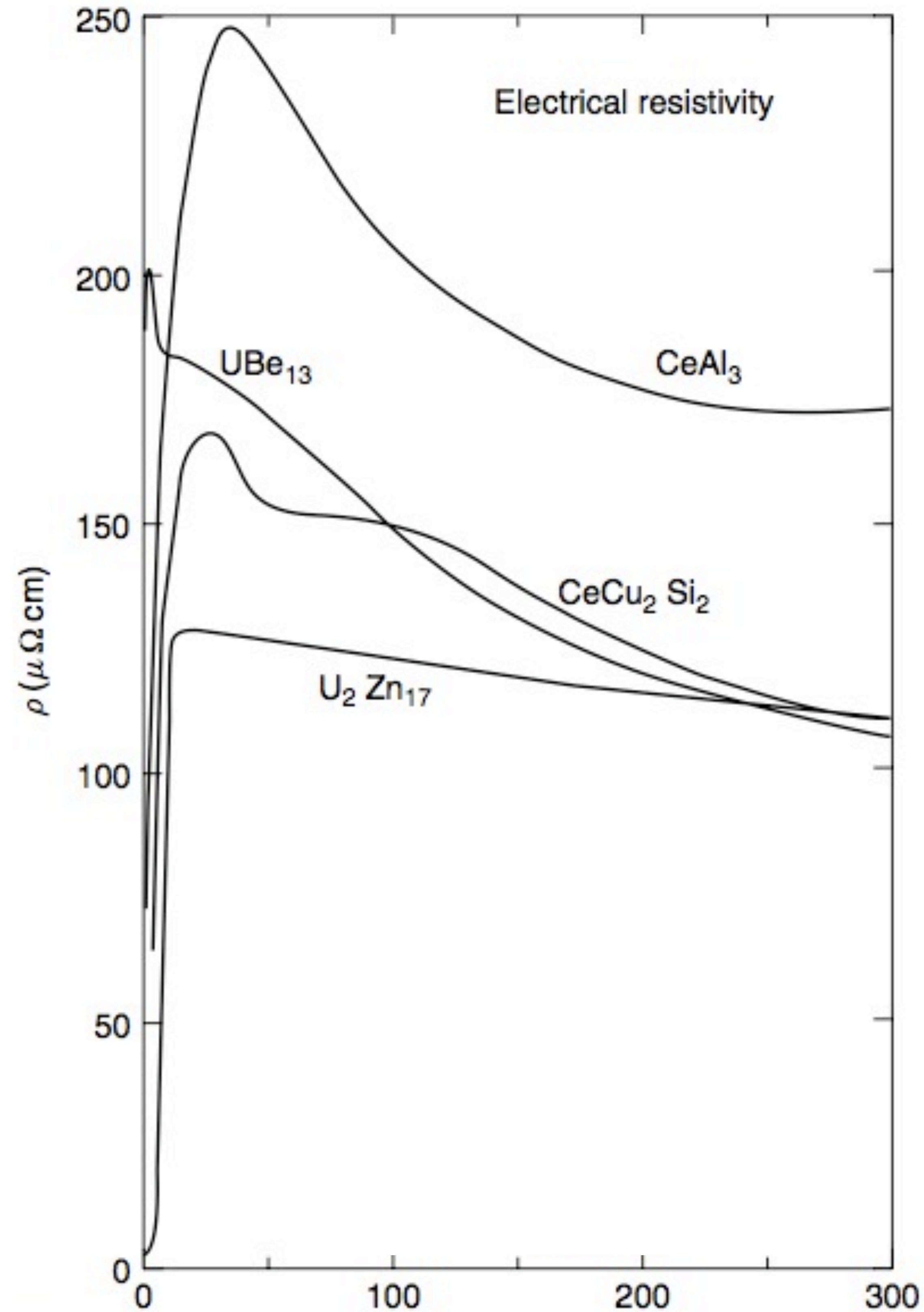

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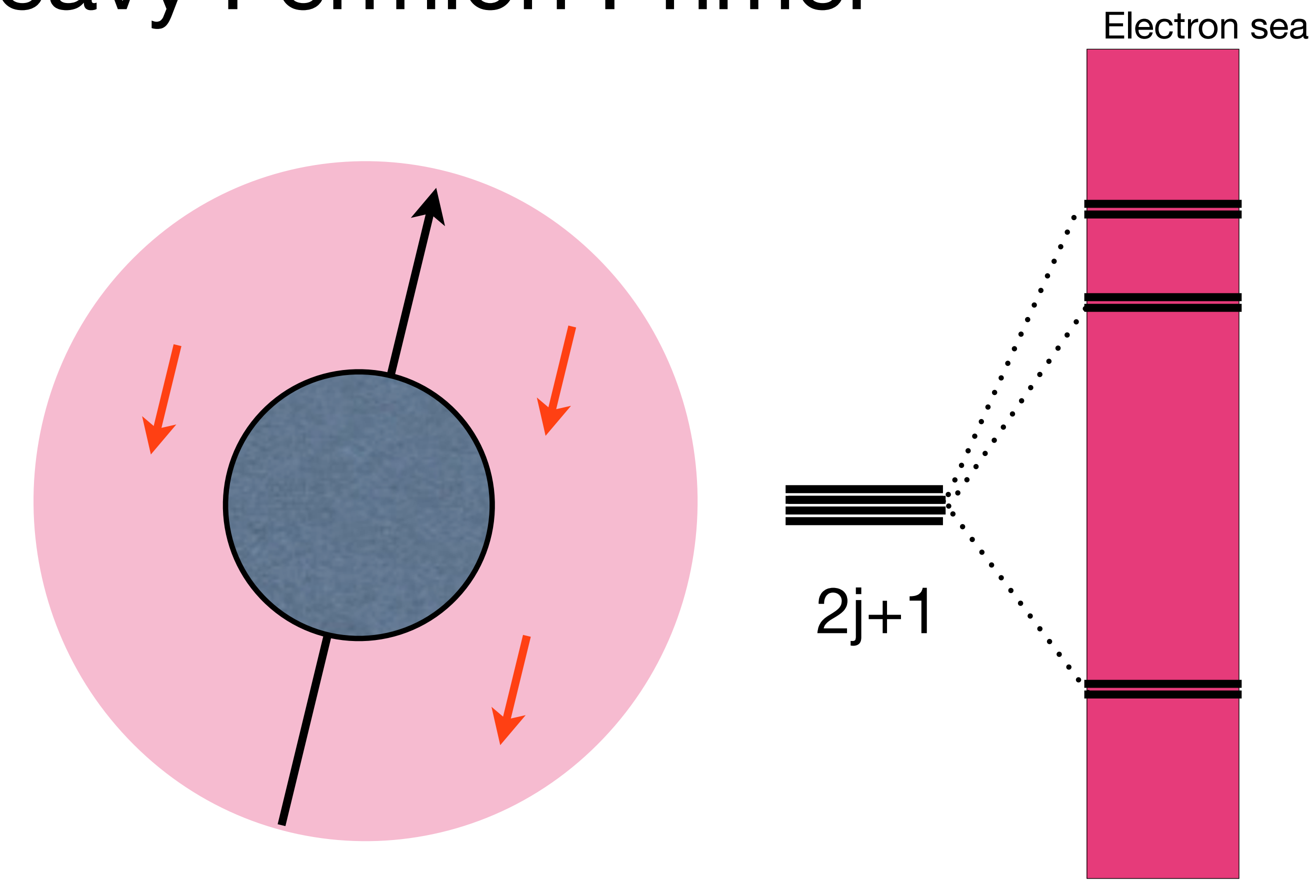

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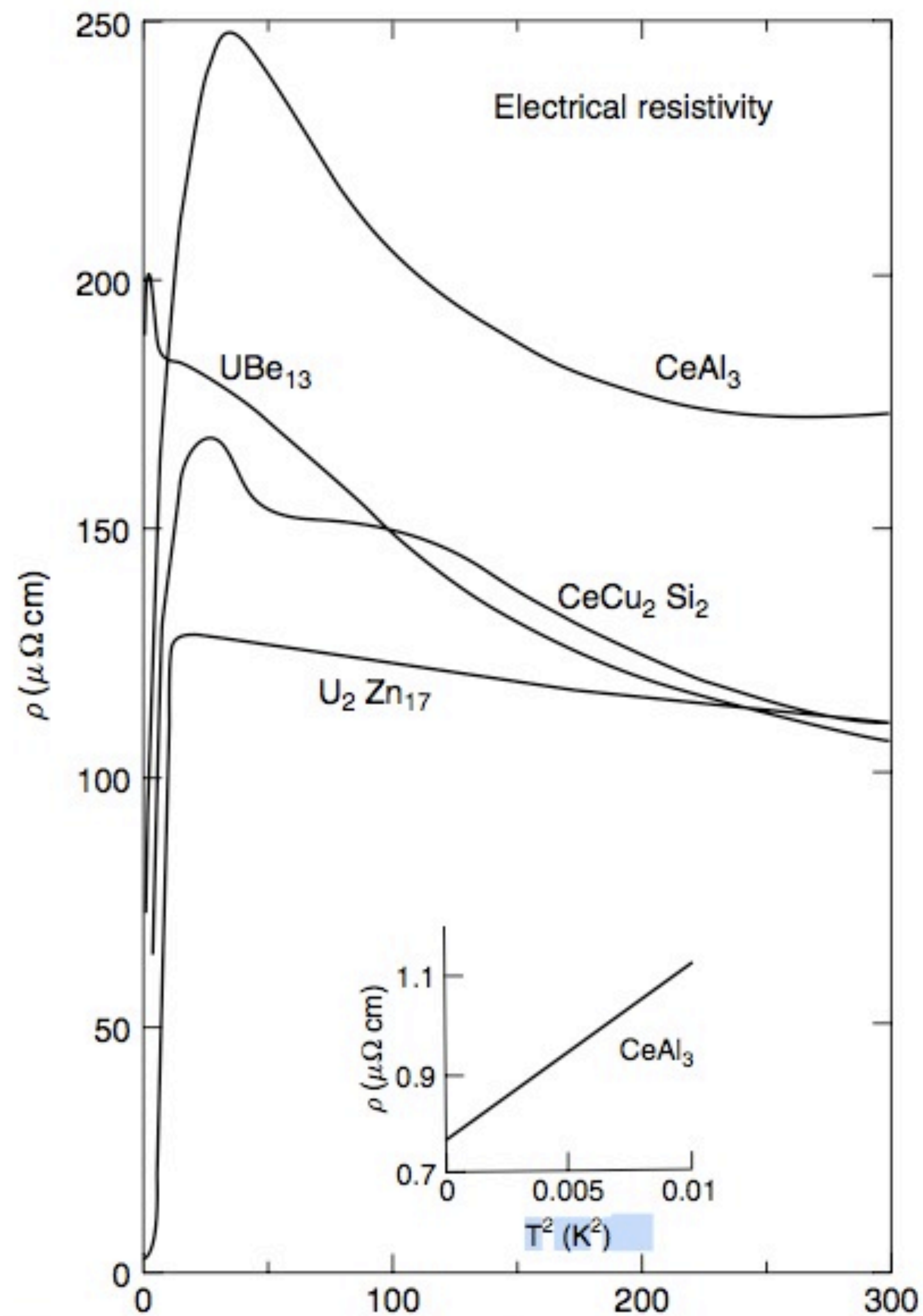
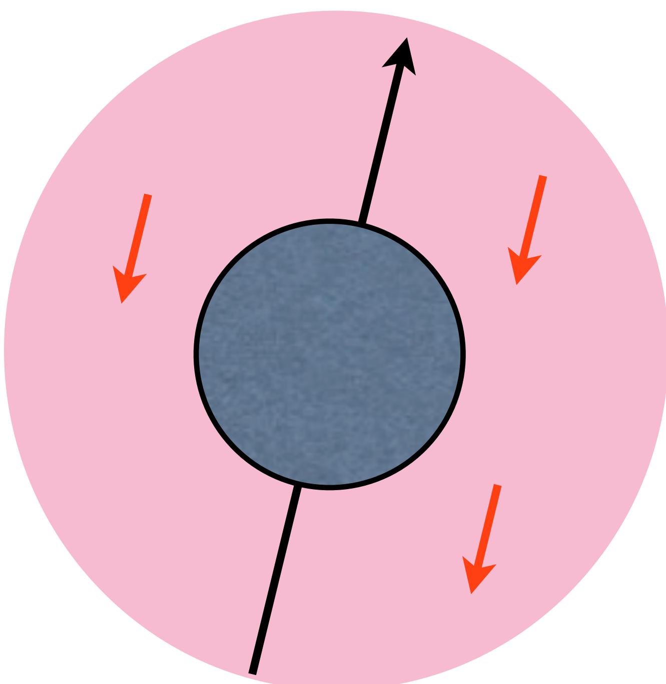


$$\rho(T) = \rho_0 + AT^2$$

Coherent Heavy Fermions

Heavy Fermion Primer



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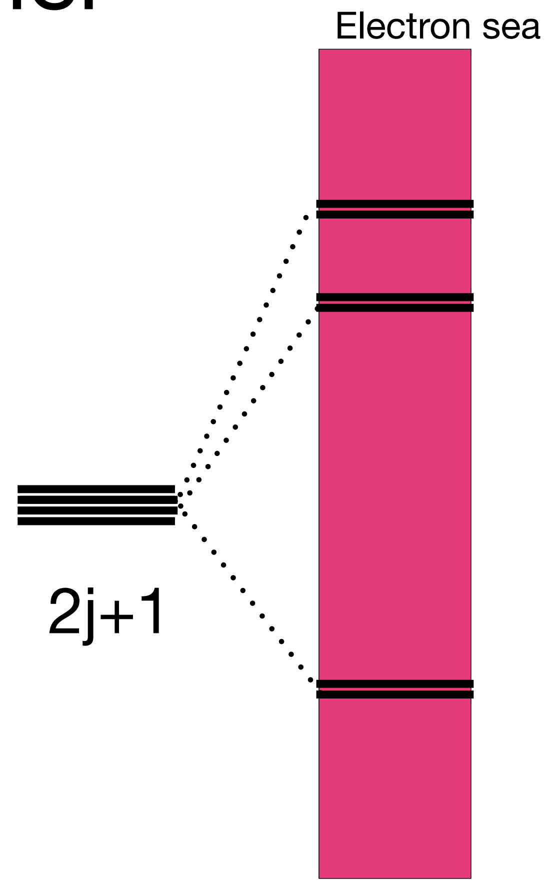
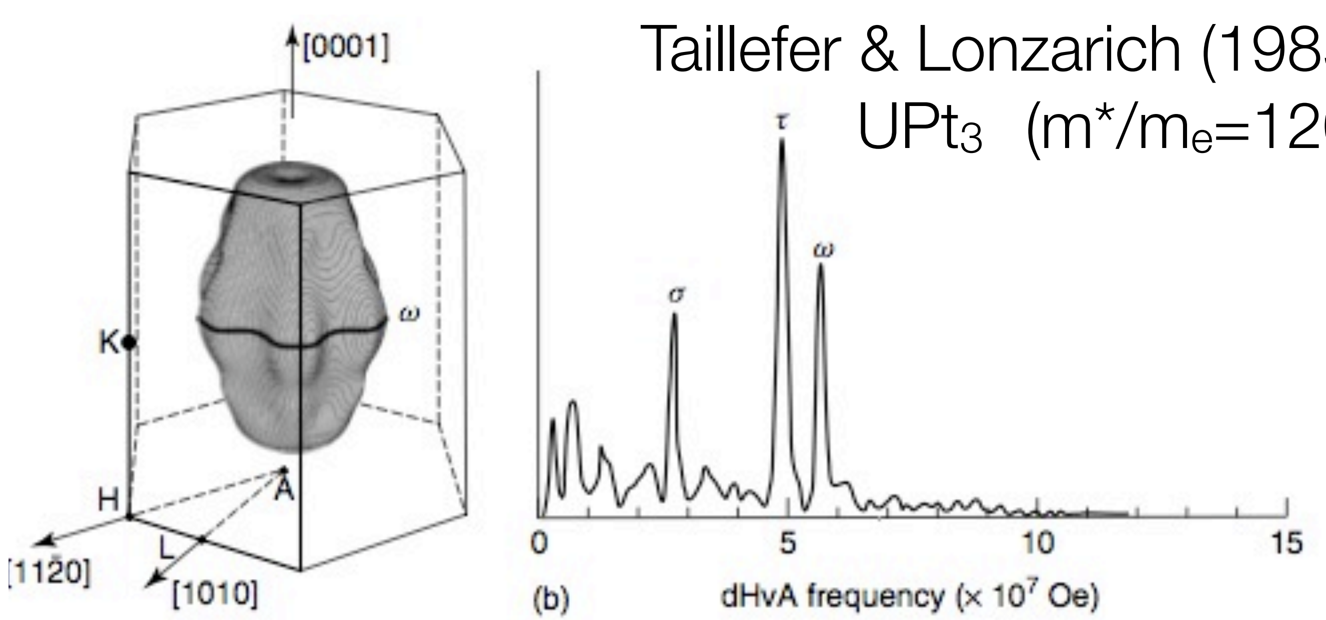
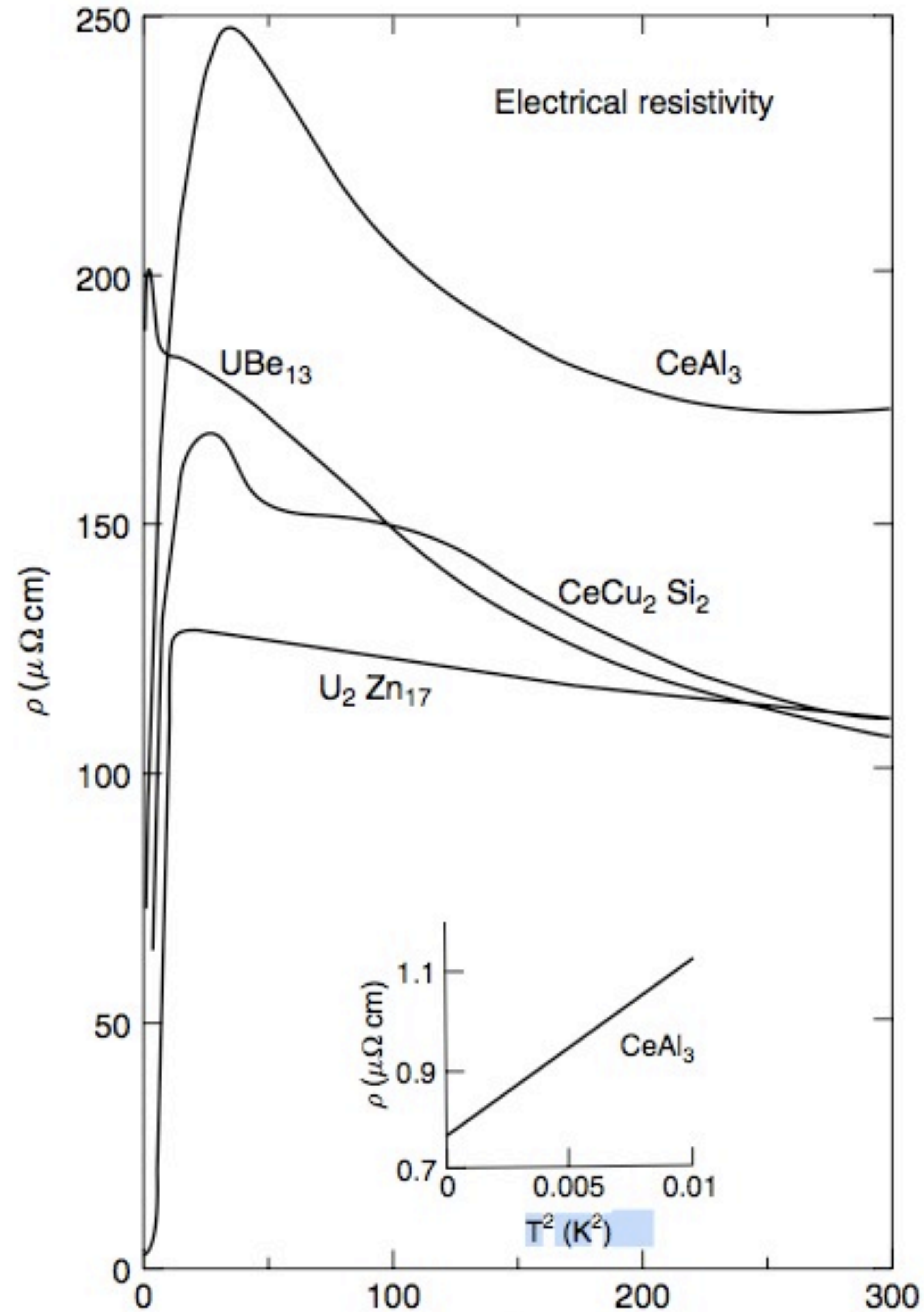




Taillefer & Lonzarich (1985)
UPt_3 (m^*/m_e=120)



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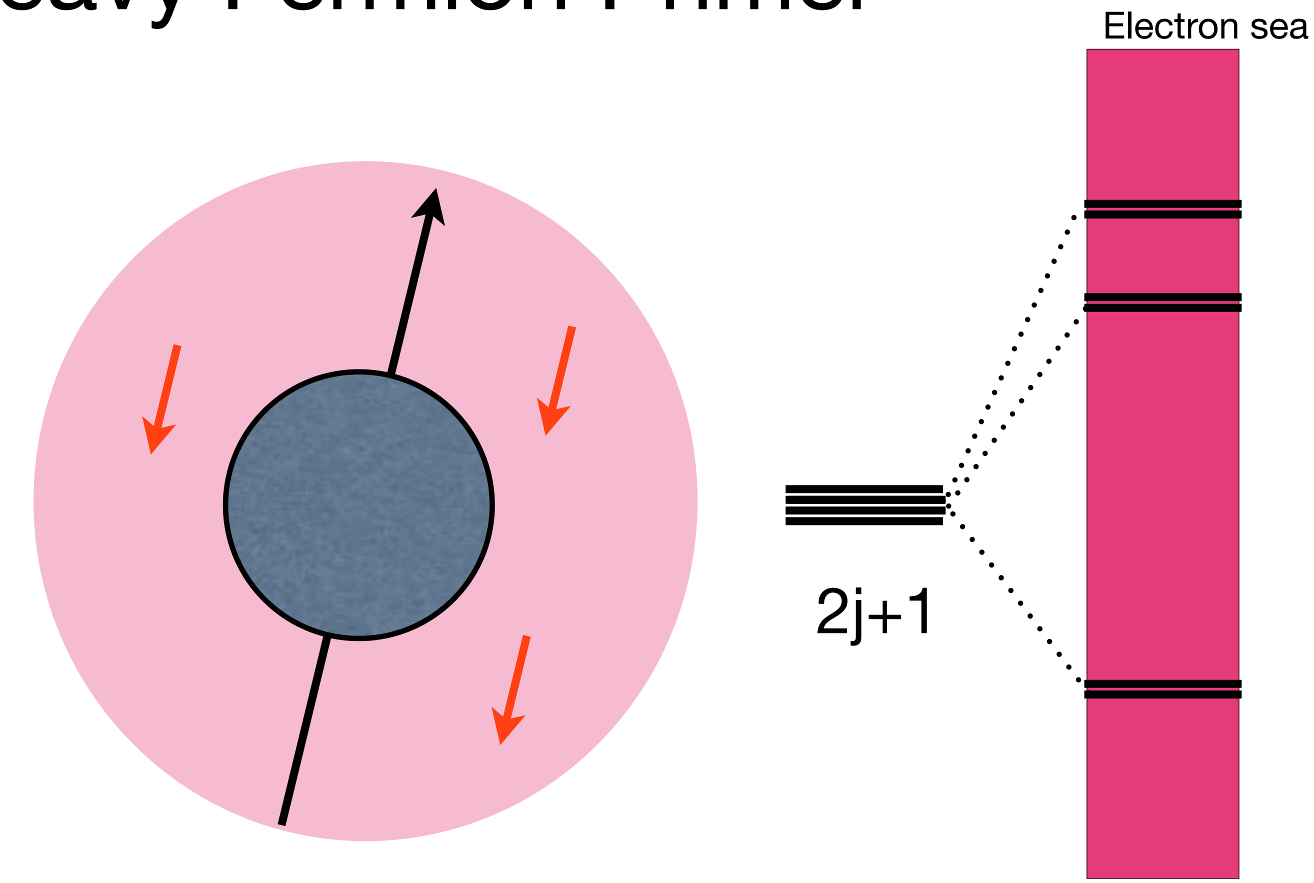

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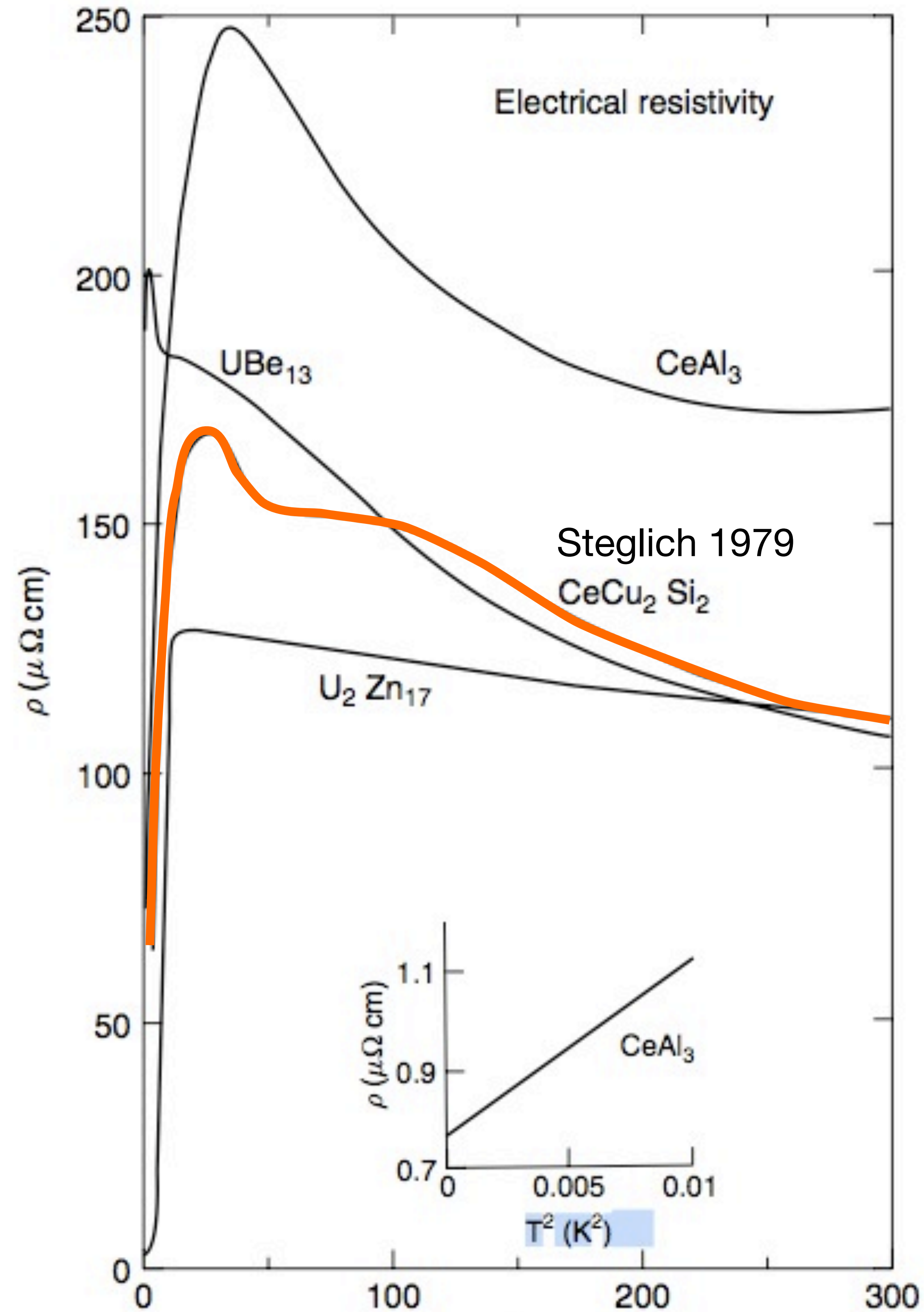

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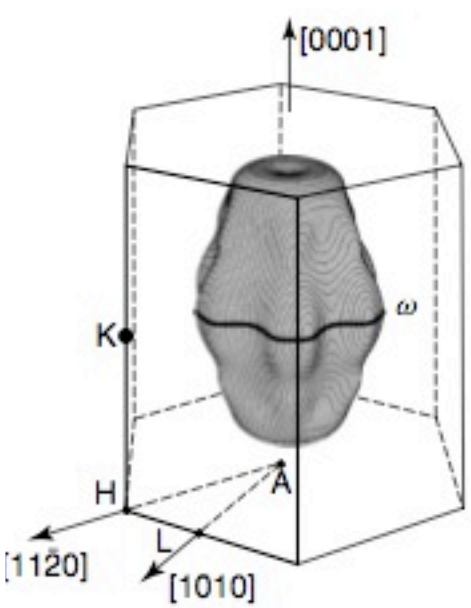

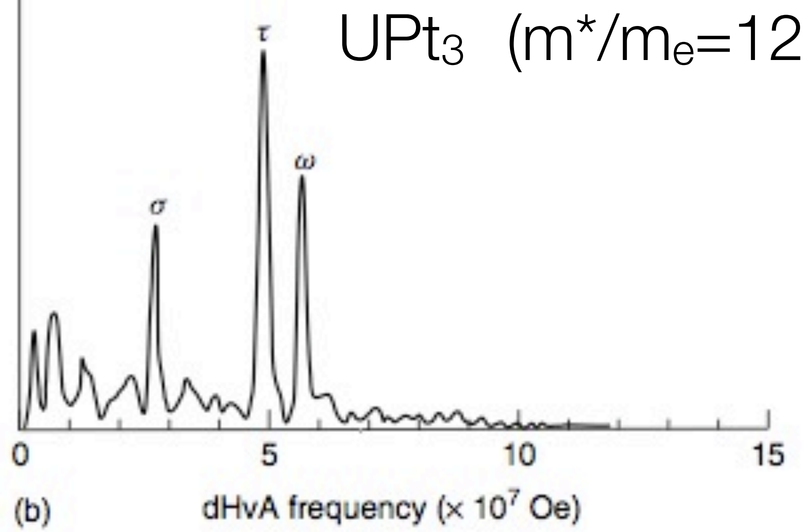

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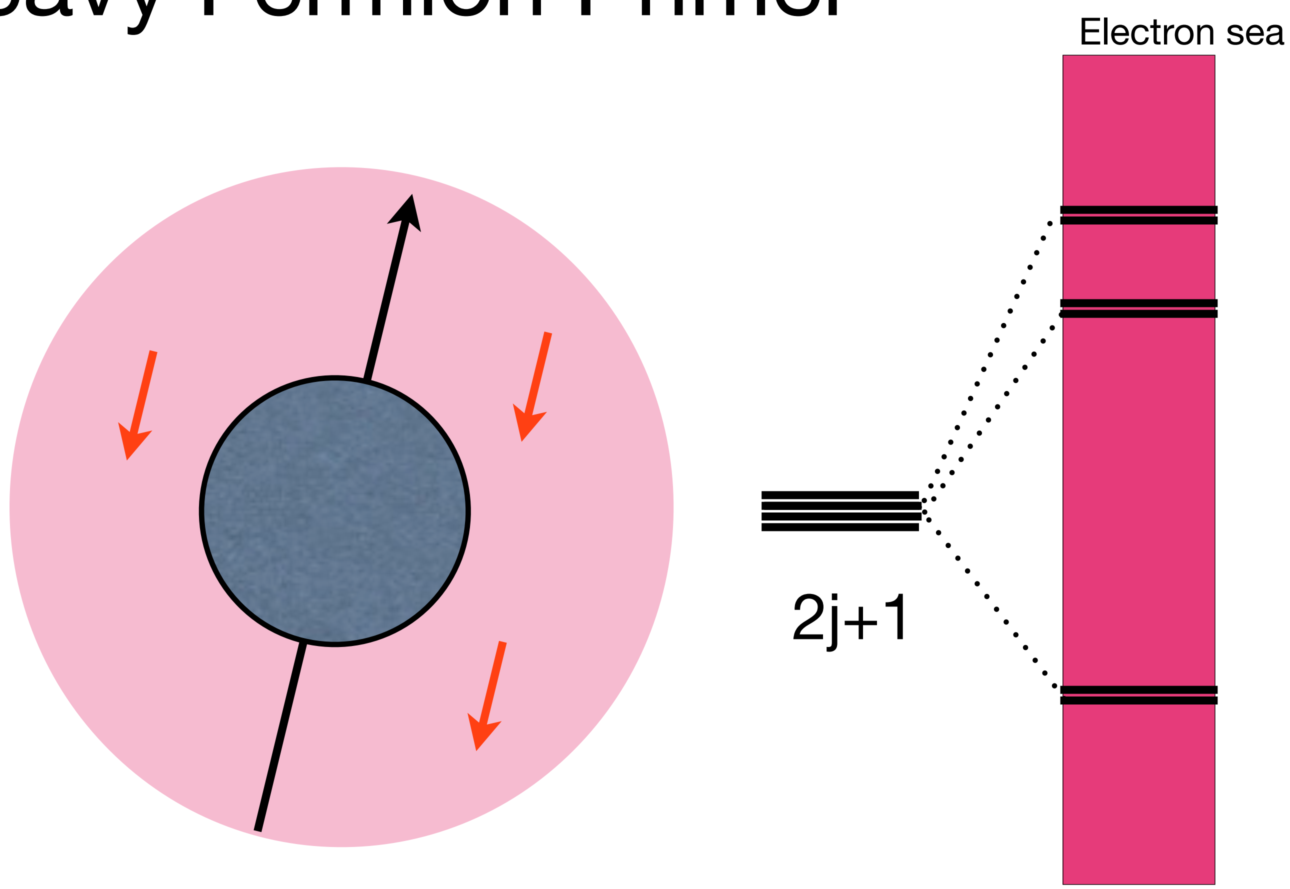

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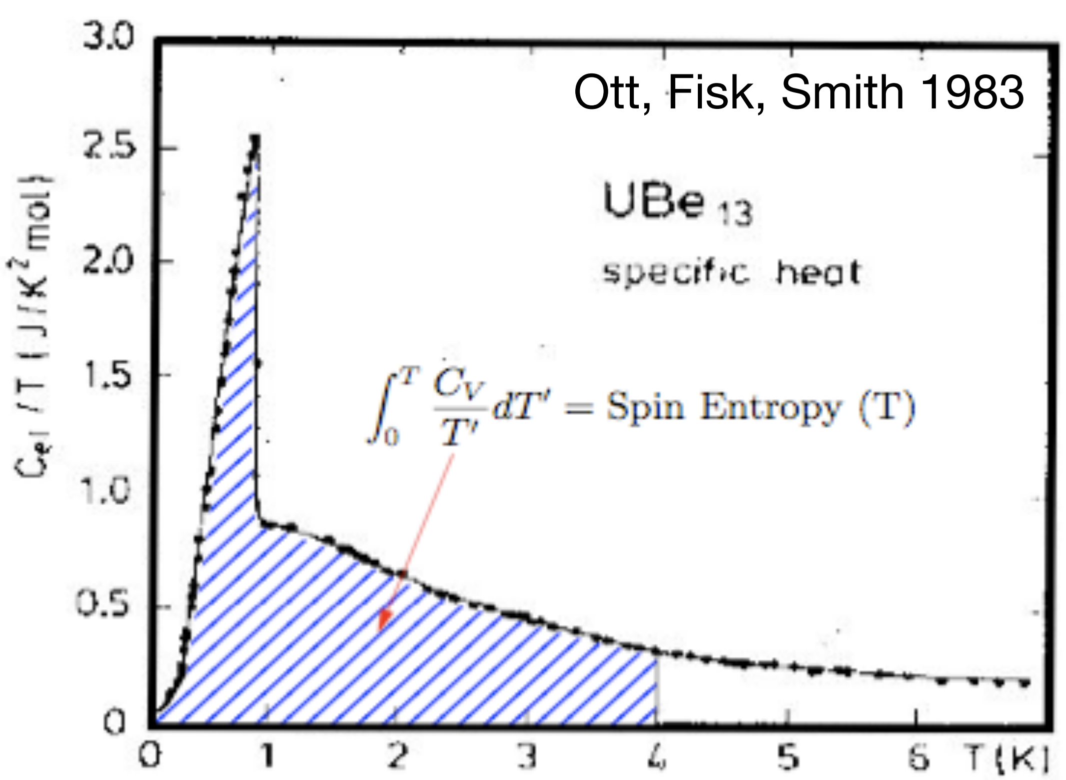

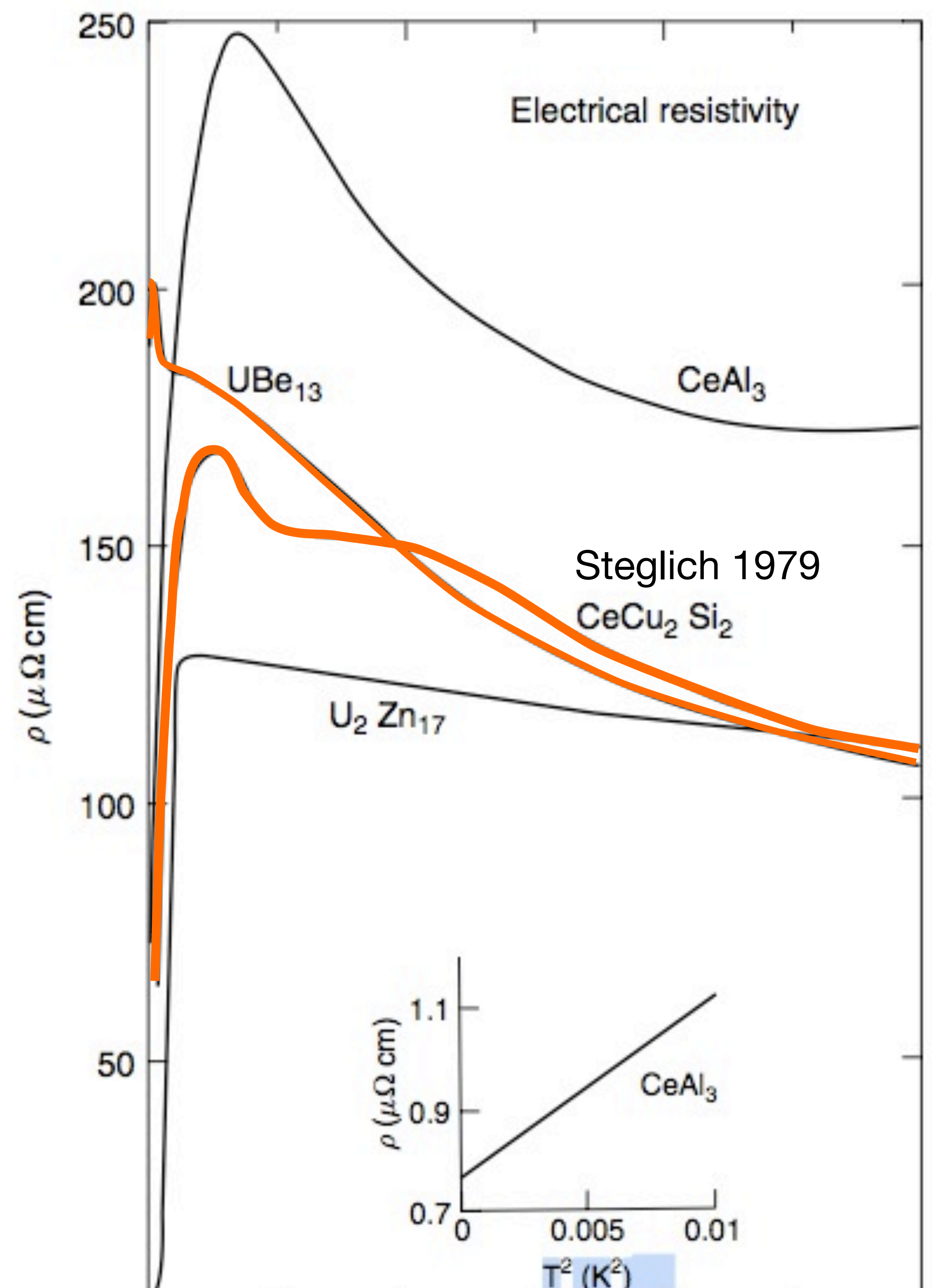

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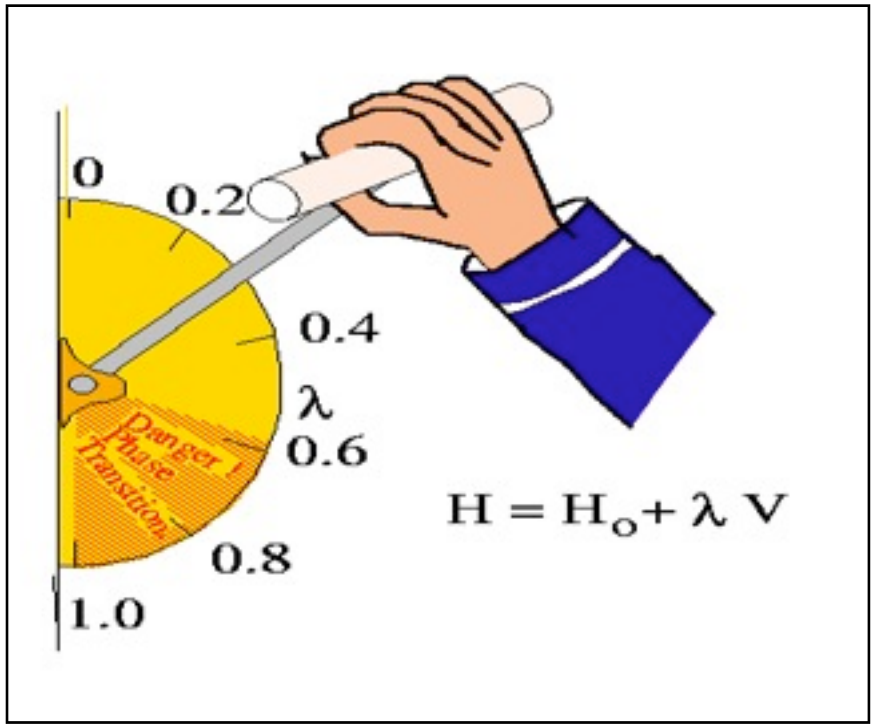
Coherent Heavy Fermions

Landau Fermi Liquid Theory :

x



Interactions can be turned on <u>adiabatically (no entropy change)</u>, preserving the excitation spectrum

Landau Fermi Liquid Theory :

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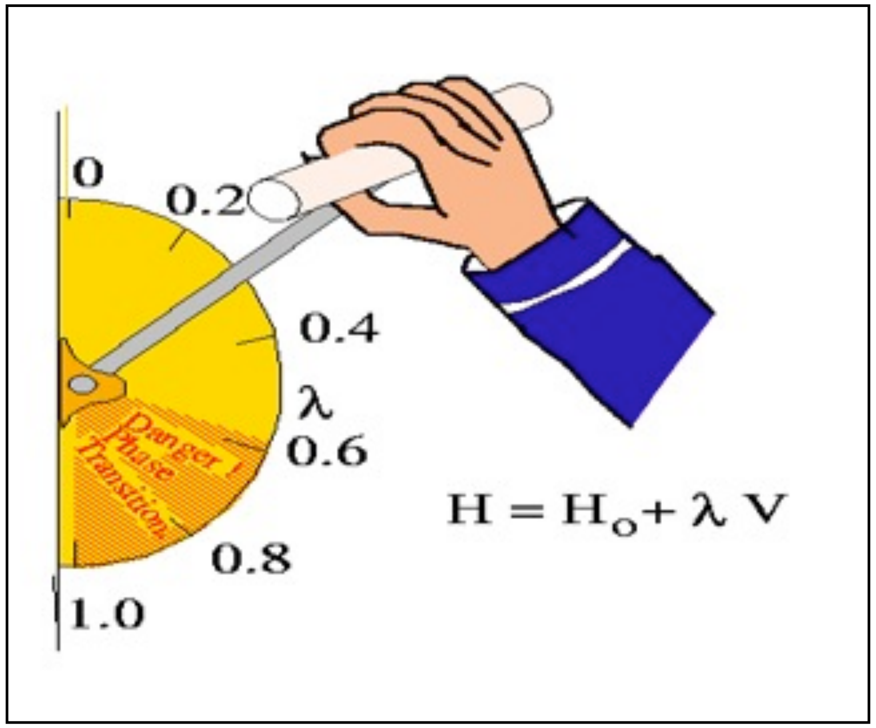

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States labelled by same quantum nos as non-interacting Fermi liquid

$$\Psi = |n_{\mathrm{p}_1\sigma_1},\ n_{\mathrm{p}_2\sigma_2}, \ldots\rangle$$

Landau Fermi Liquid Theory :

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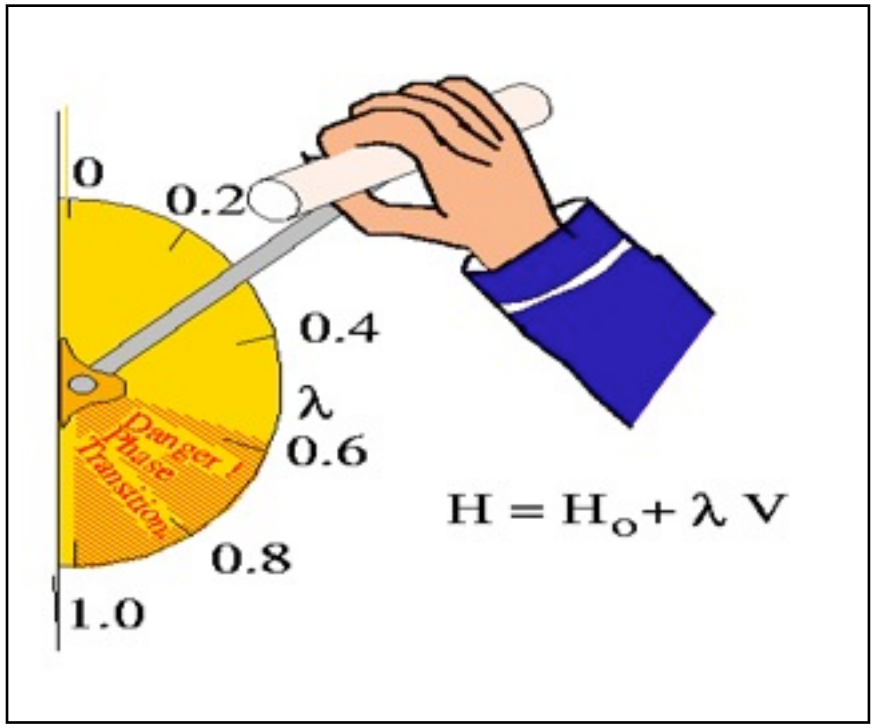

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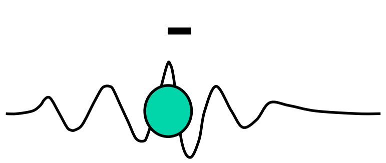
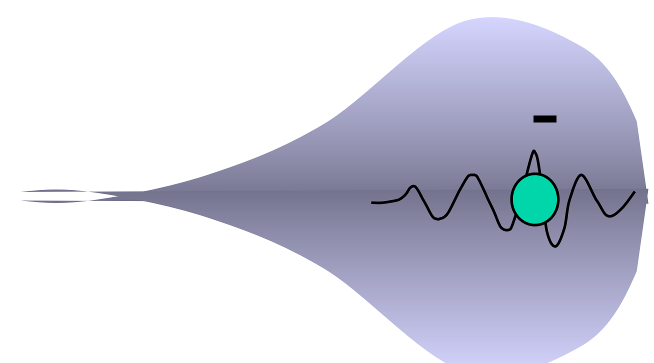


Interactions $\longrightarrow$ adiabatically

“Quasiparticle”



$|e^-\rangle$ $\qquad\qquad$ $|qp^-\rangle$

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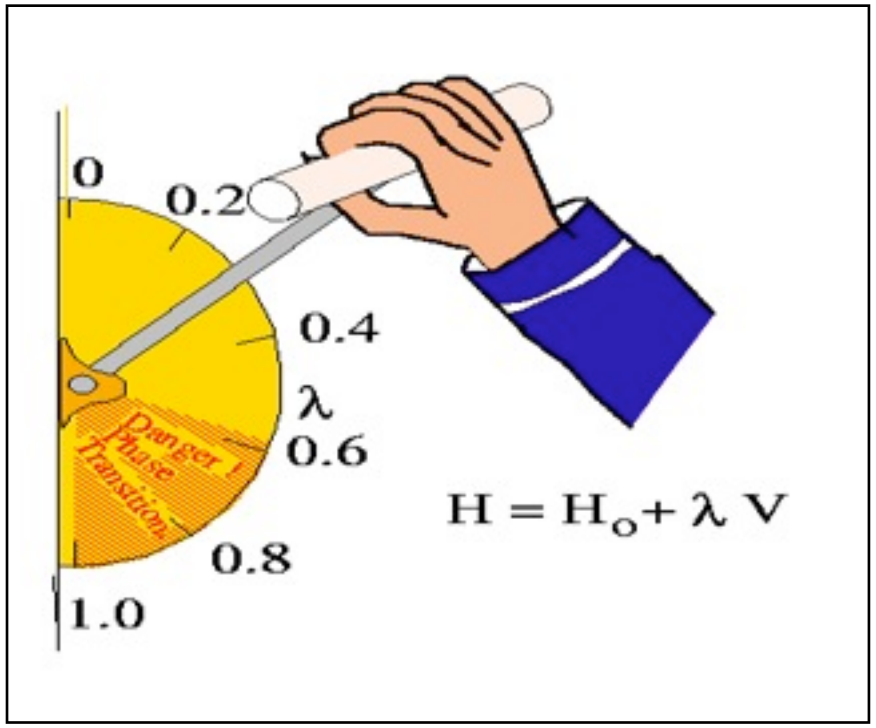

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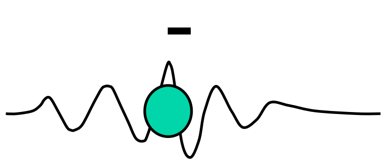
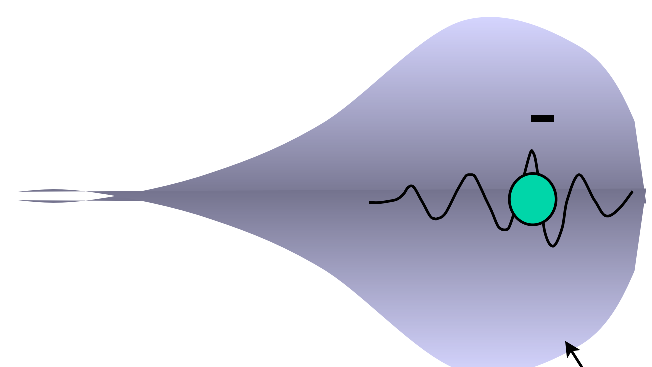
$$\Psi = \left| n_{\mathrm{p}_1\sigma_1}, \; n_{\mathrm{p}_2\sigma_2}, \ldots \right\rangle$$

"Quasiparticle"



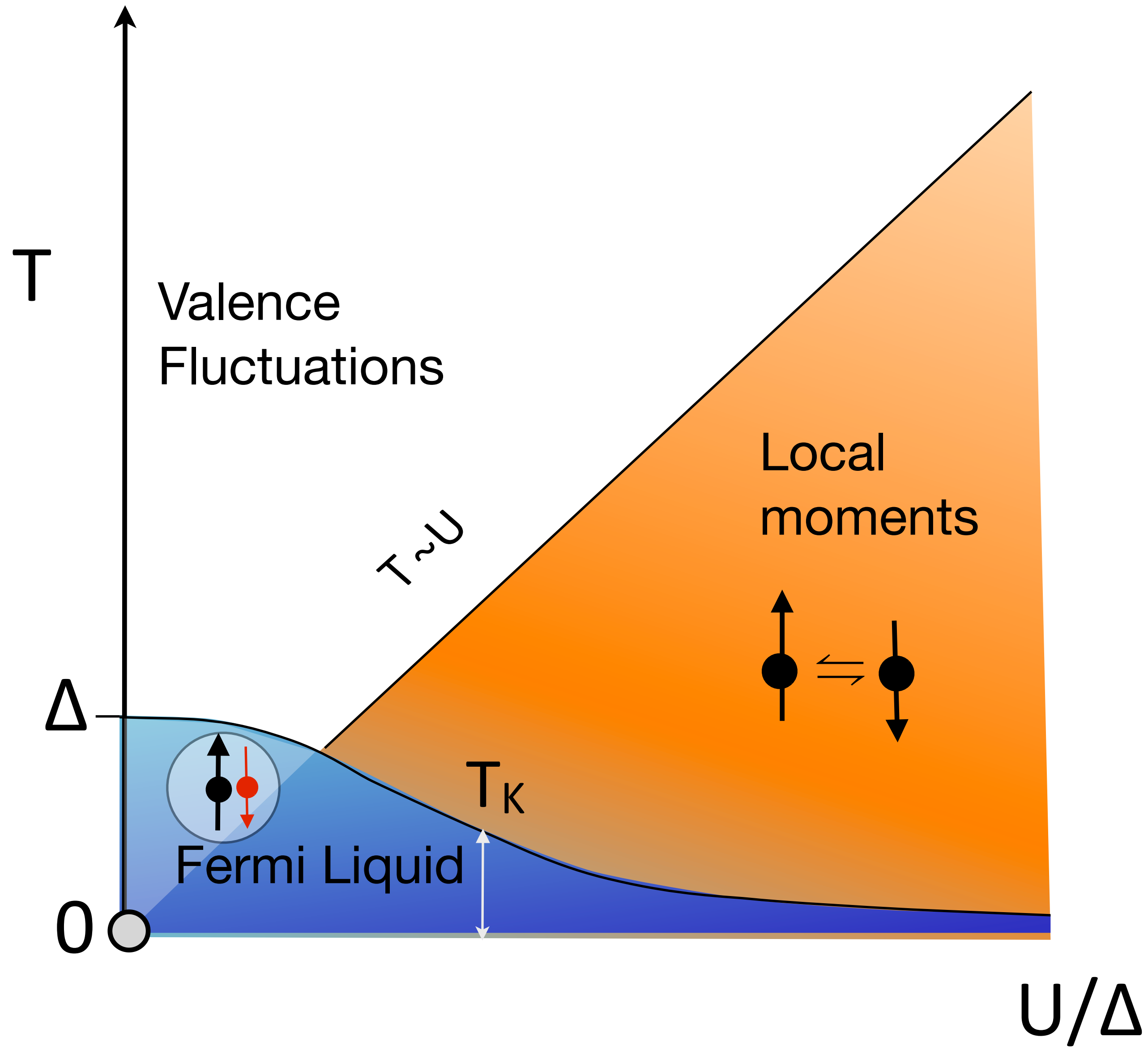
Interactions adiabatically



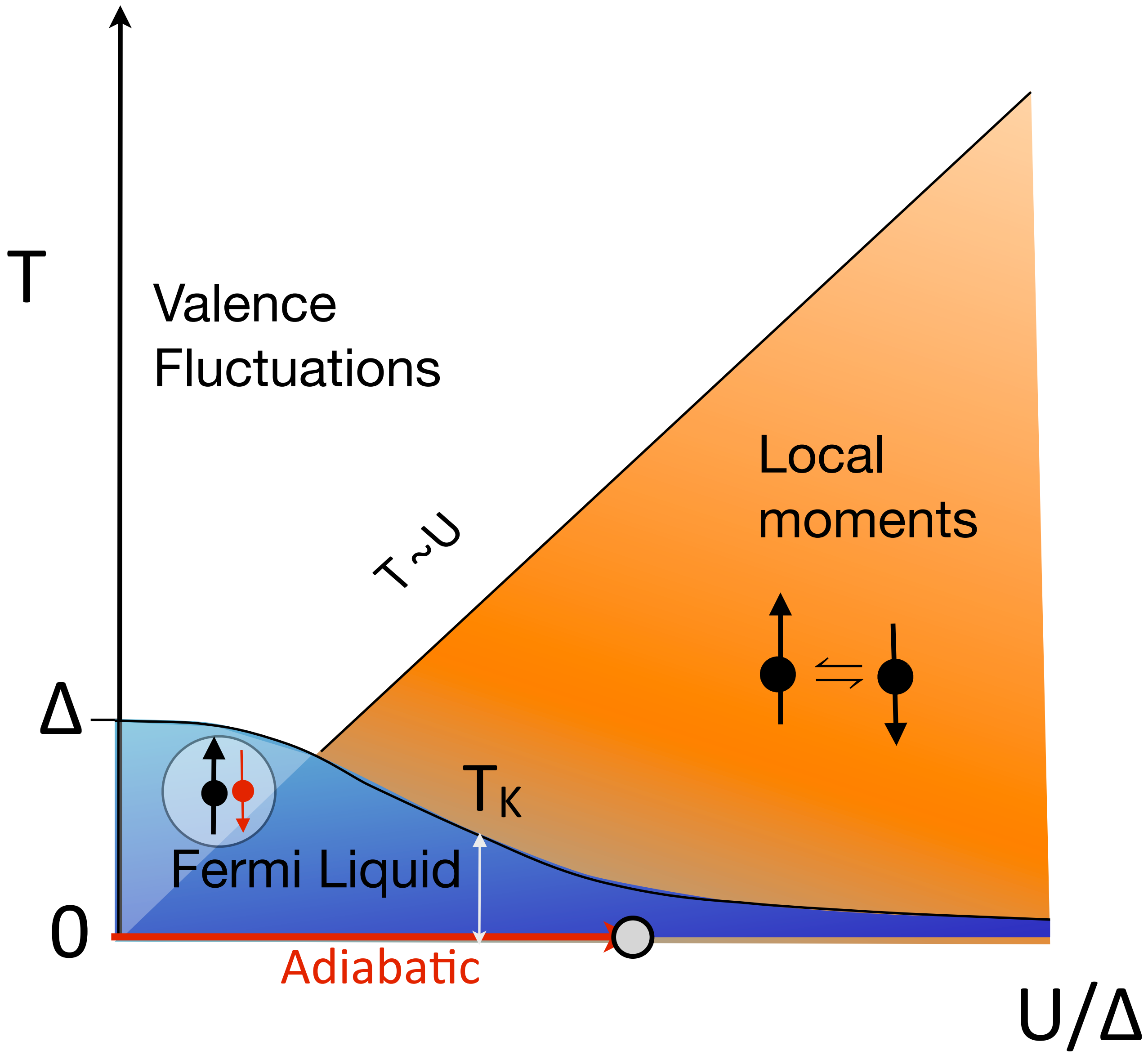
$$\left| e^- \right\rangle \qquad \left| qp^- \right\rangle$$

$$\frac{m^*}{m} = \frac{N^*(0)}{N(0)} = 1 + F_1^s$$

Adiabaticity and Scaling



Adiabaticity and Scaling



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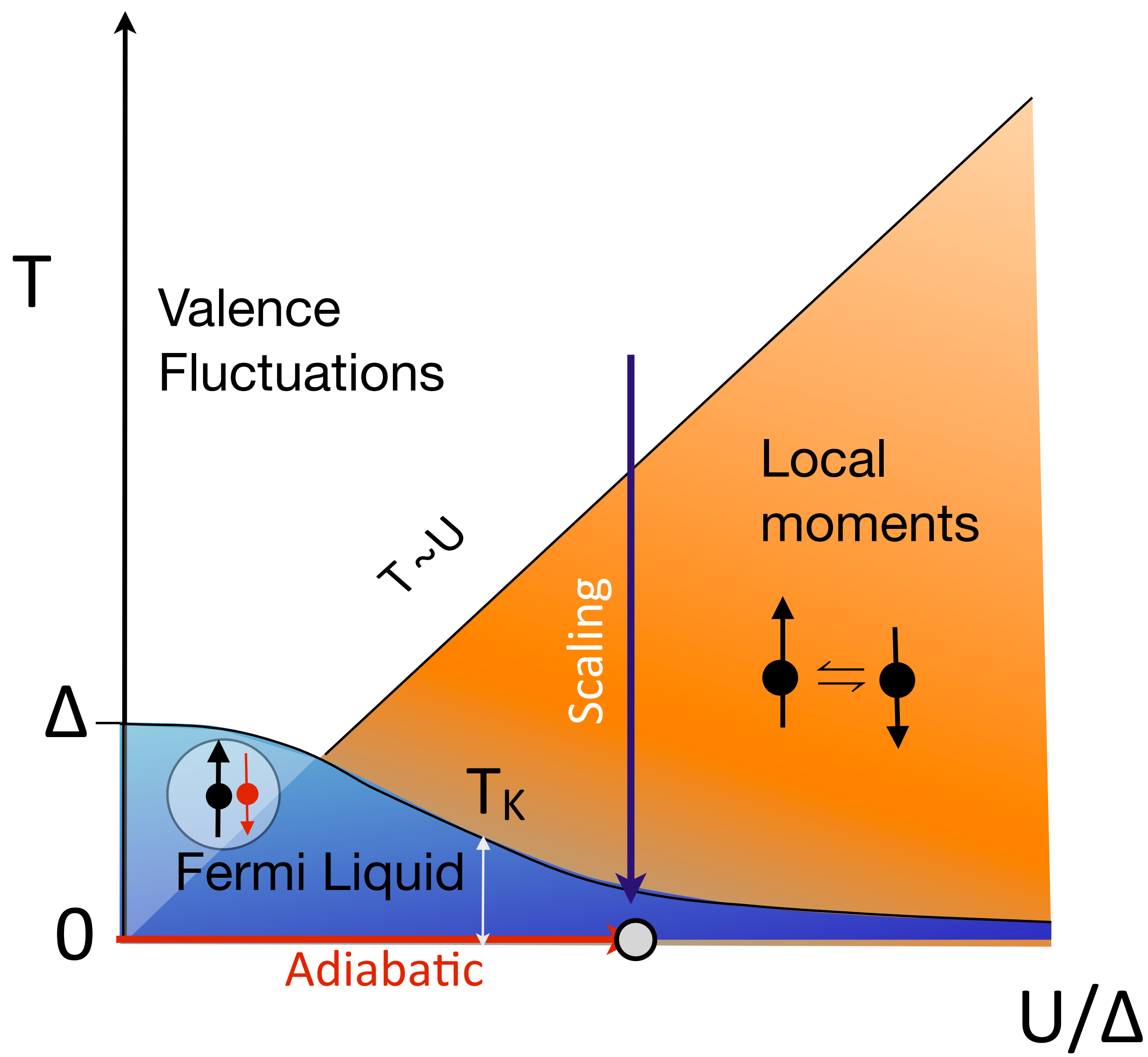

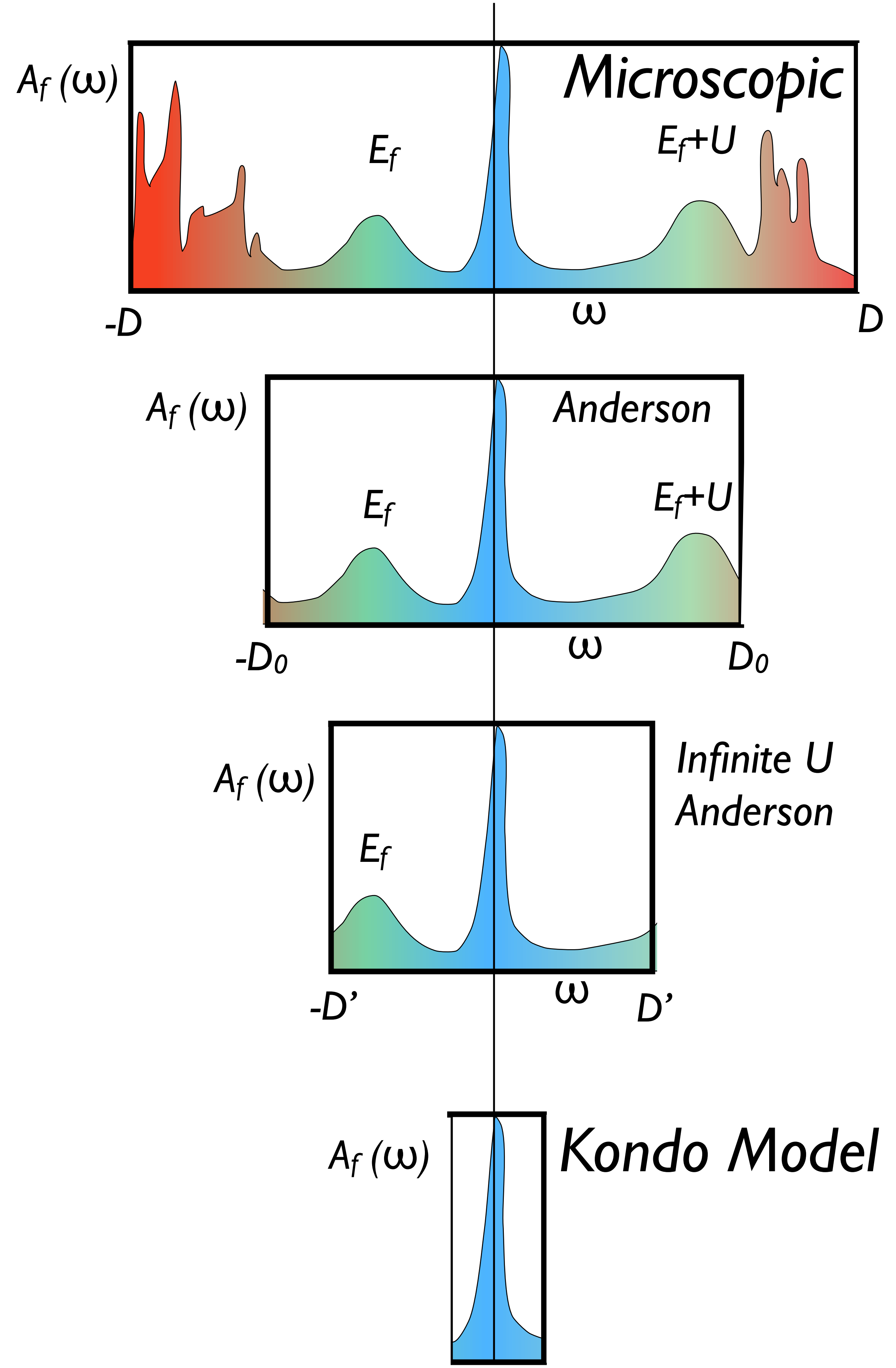

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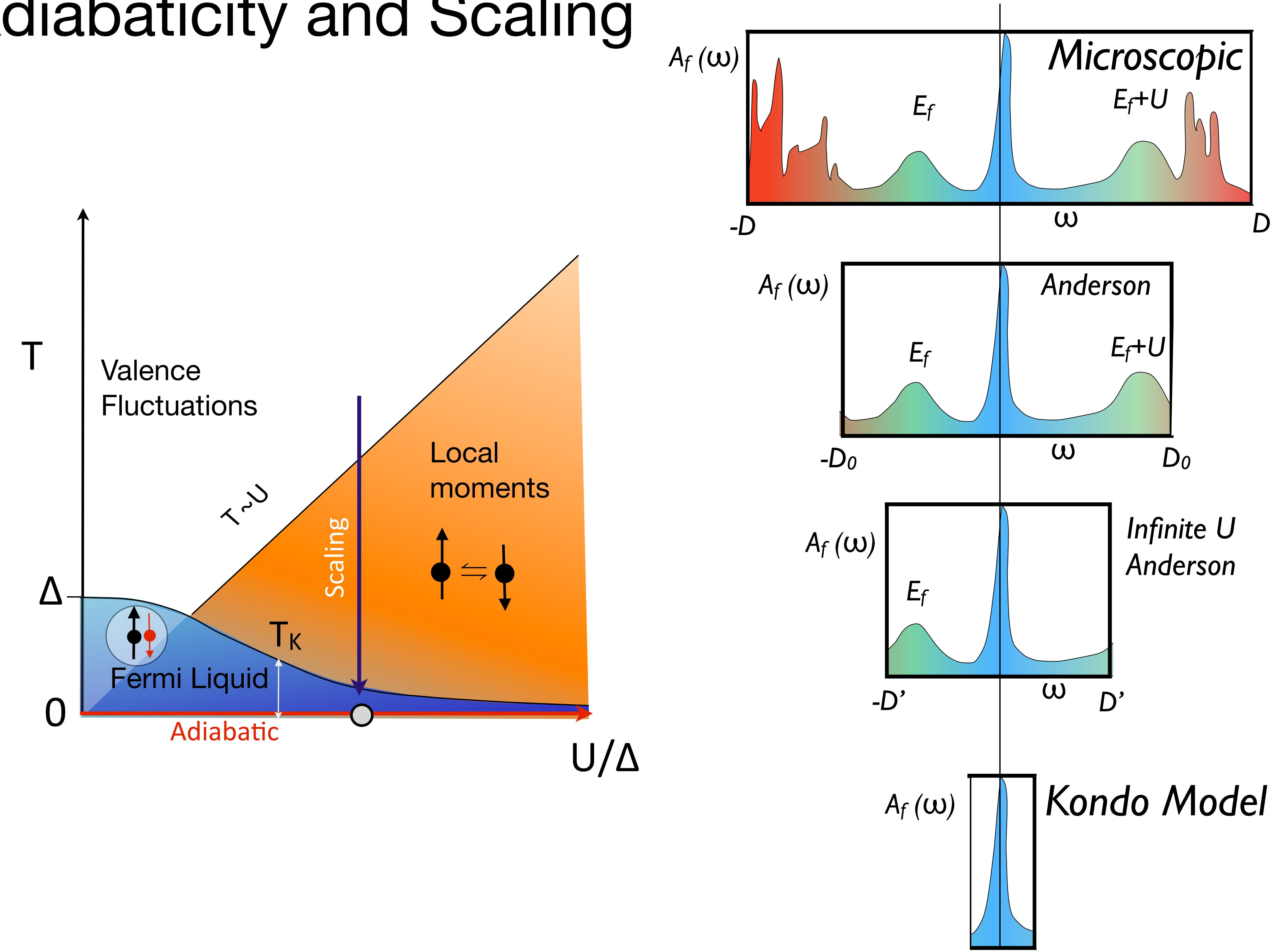

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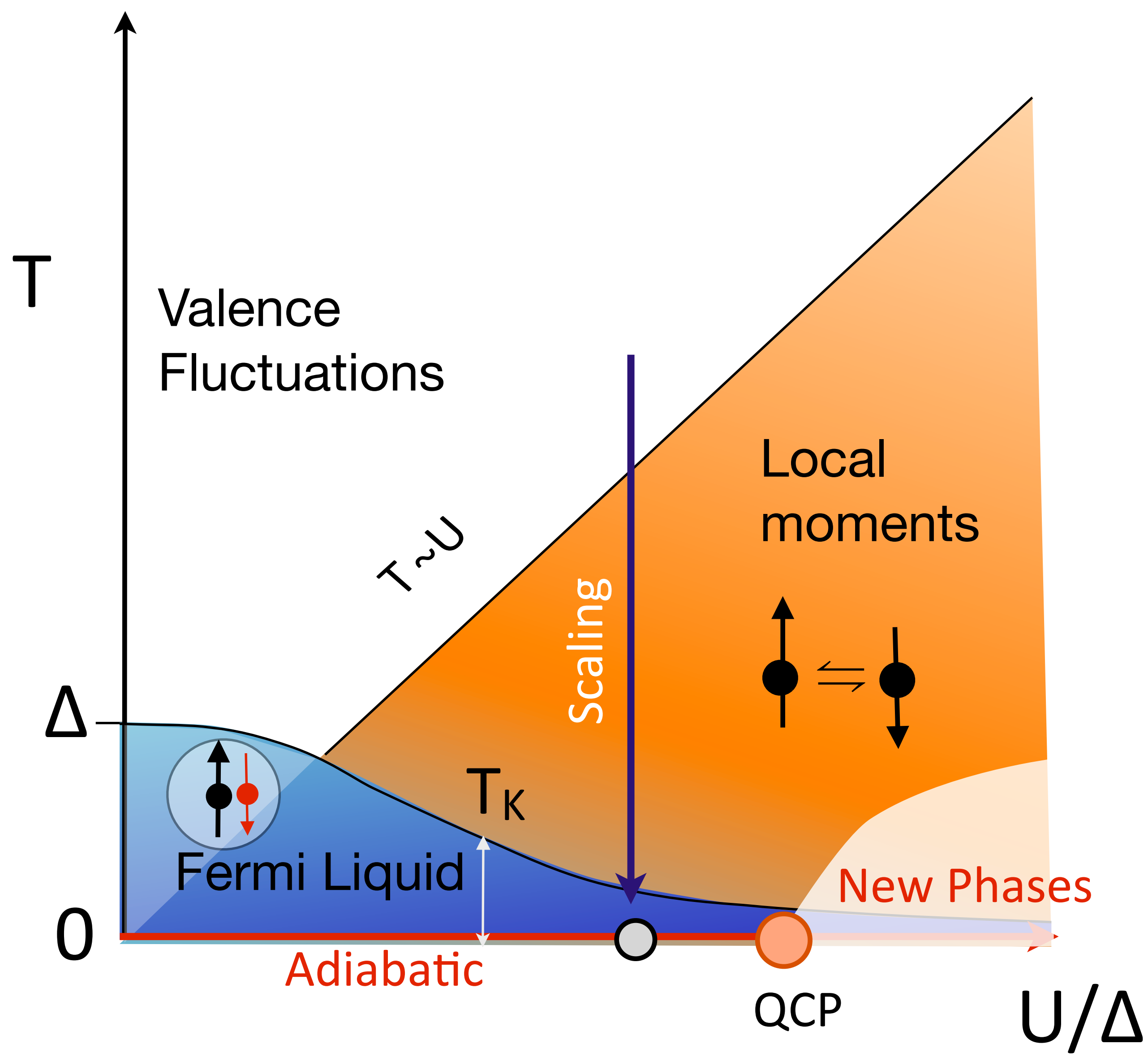

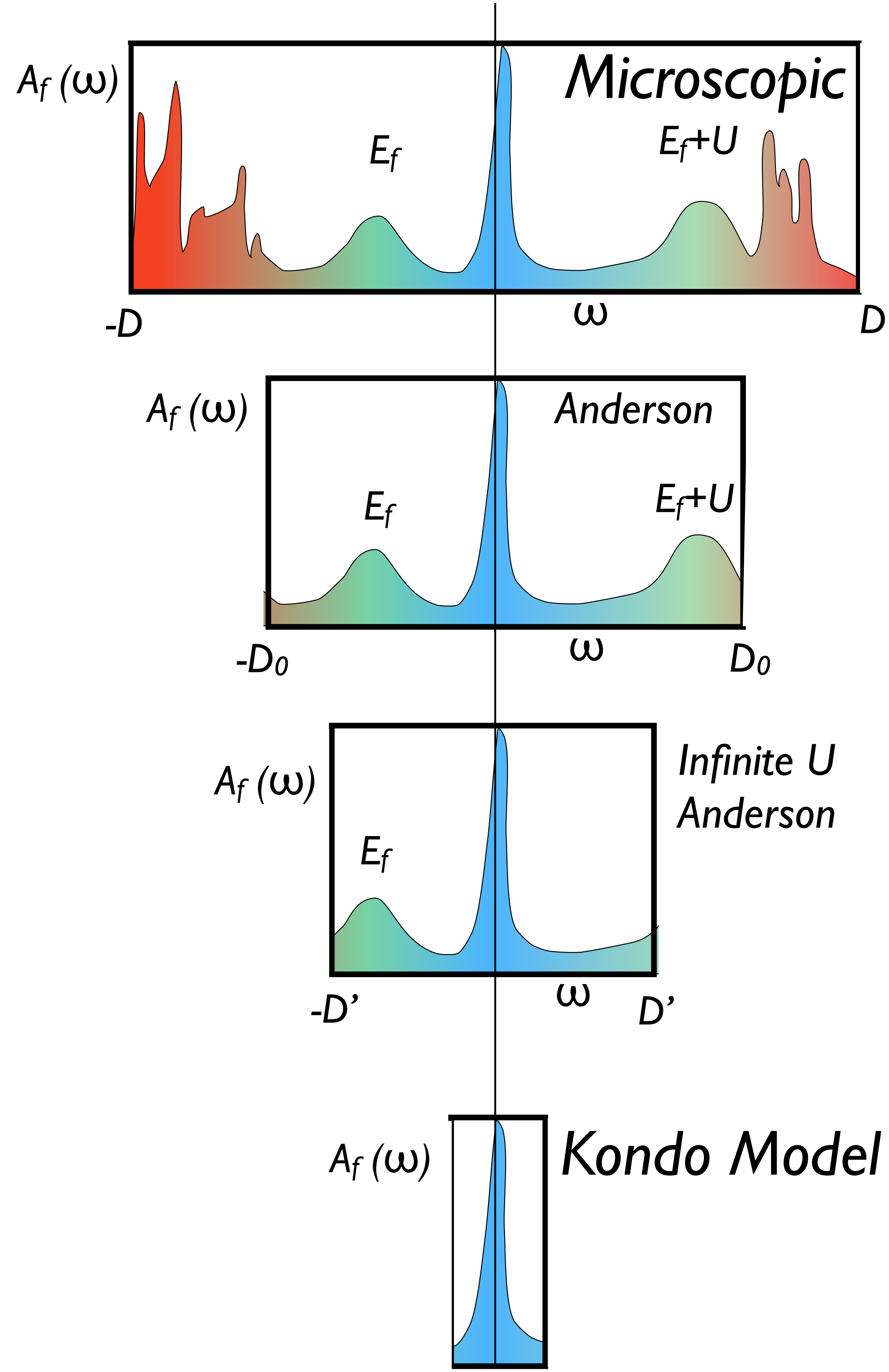

$$H = \sum \epsilon_k c^{\dagger}_{k\sigma} c_{k\sigma} + J(\psi^{\dagger} \vec{\sigma} \psi) \cdot \vec{S}$$

Kondo (1962)

DONIACH'S

Hypothesis.

Doniach (1977)

$$H = \sum \varepsilon_k c_{k\sigma}{}^{\dagger} c_{k\sigma} + J \sum_j (\psi^{\dagger}{}_j \vec{\sigma} \psi_j) \cdot \vec{S}_j$$

Kondo Lattice Model
(Kasuya, 1951)

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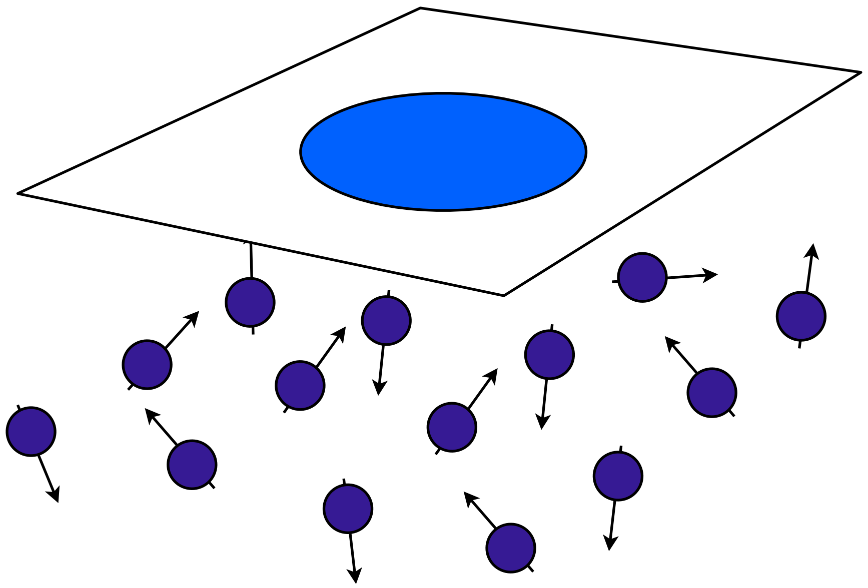

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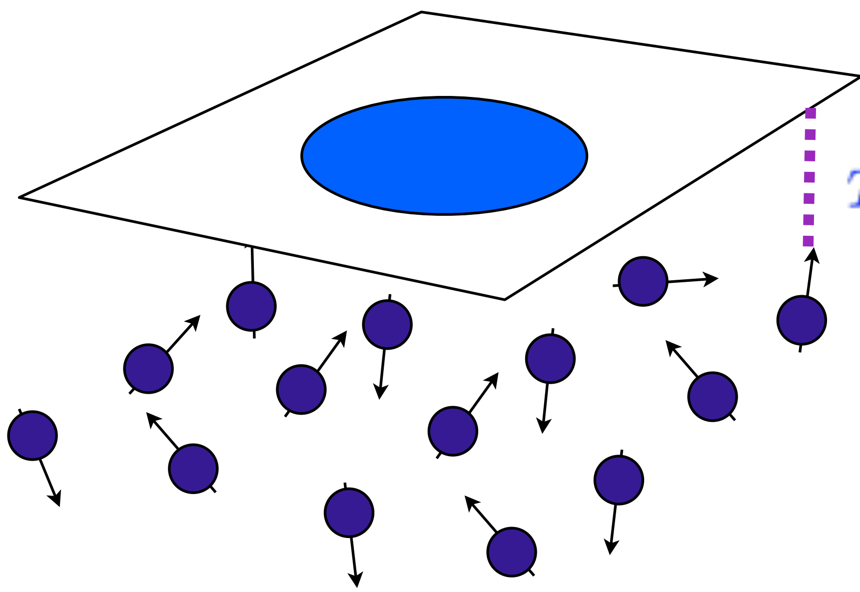

$$T_K \sim D \exp\left[-\frac{1}{2J\rho}\right]$$

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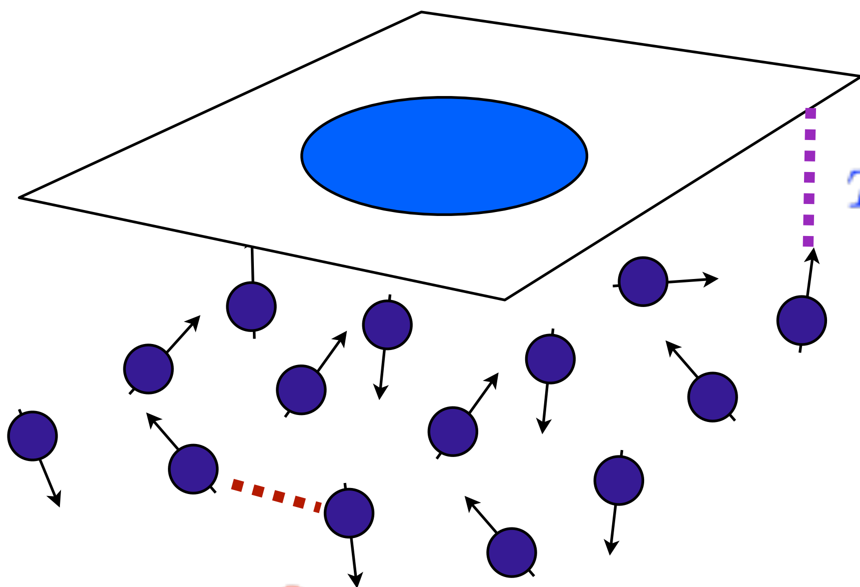

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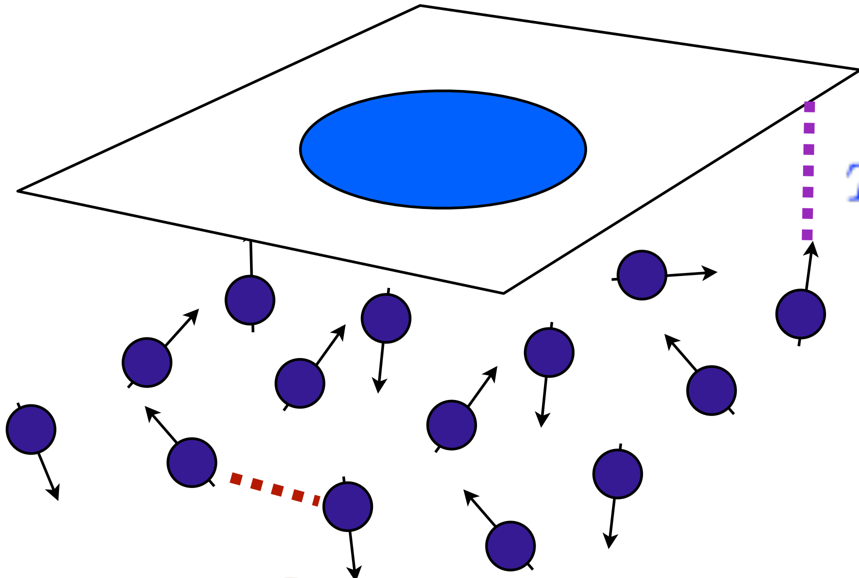

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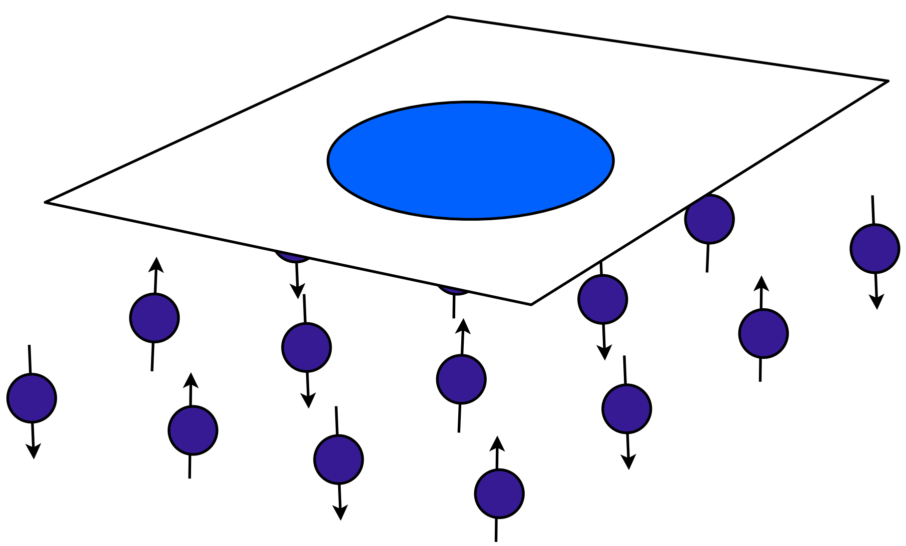

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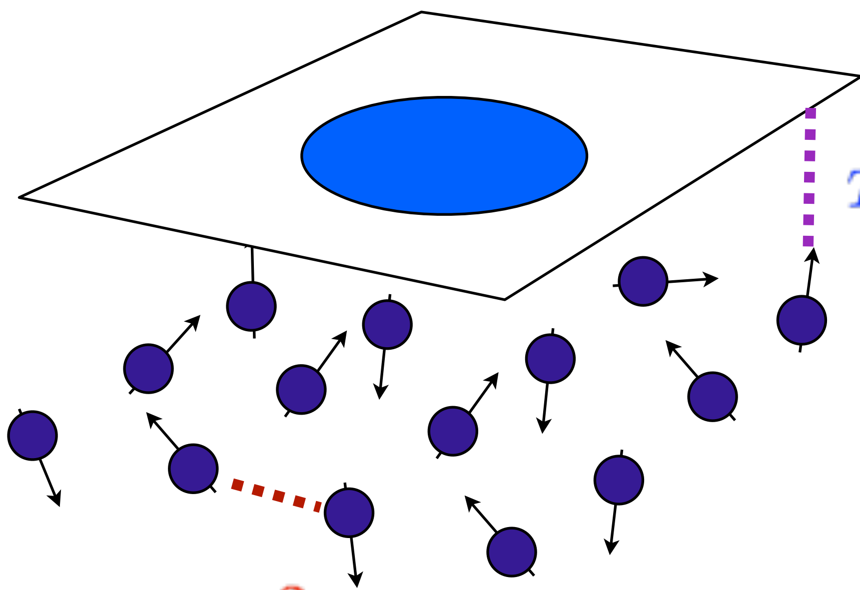

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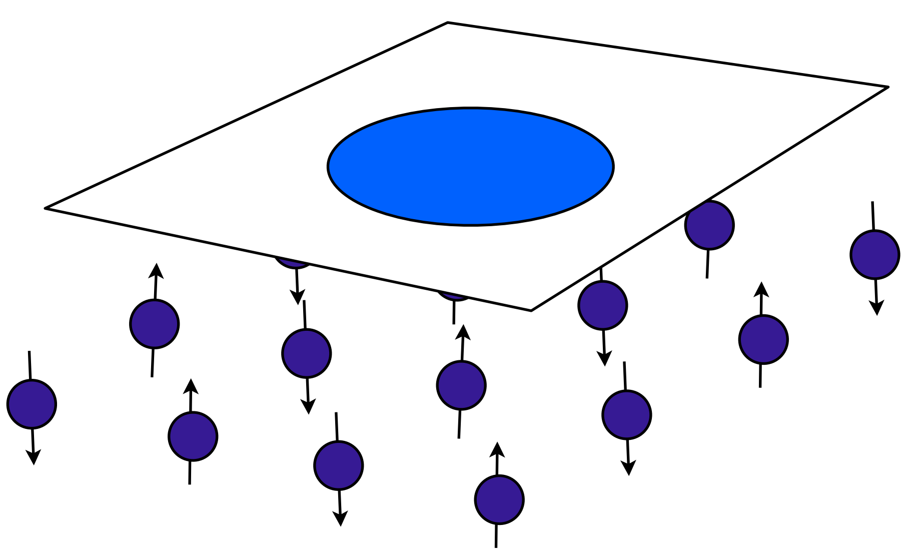
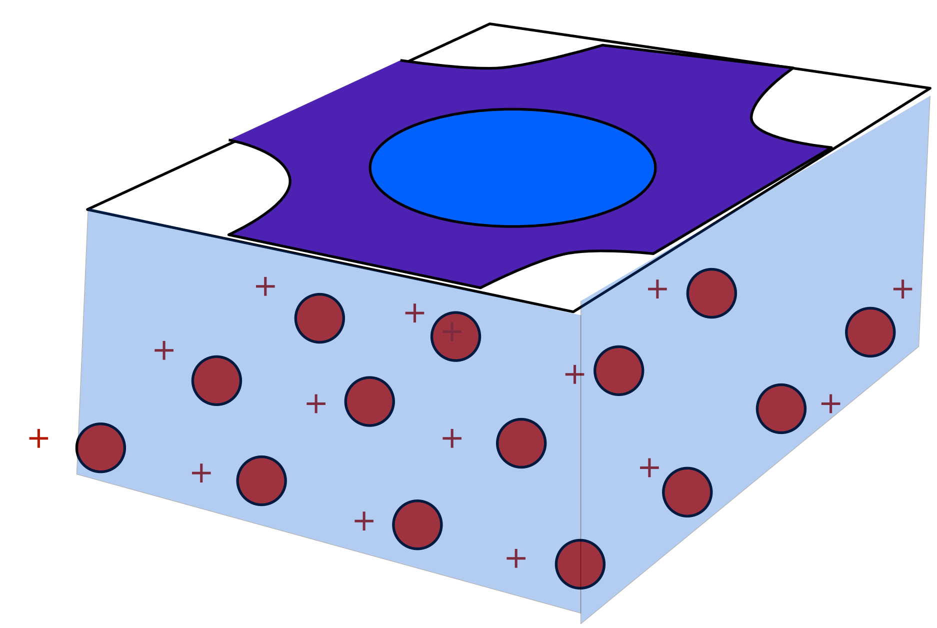


$T_{RKKY} < T_K$

Large Fermi surface of composite Fermions



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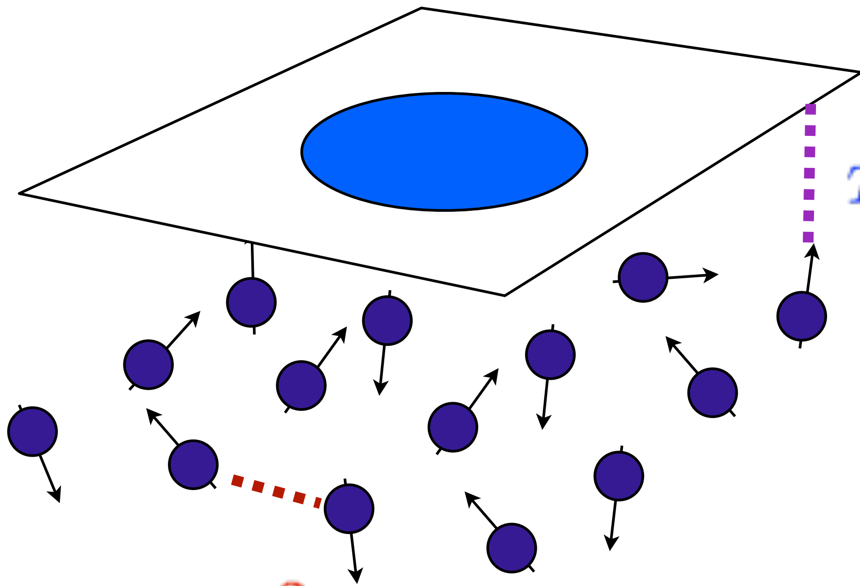

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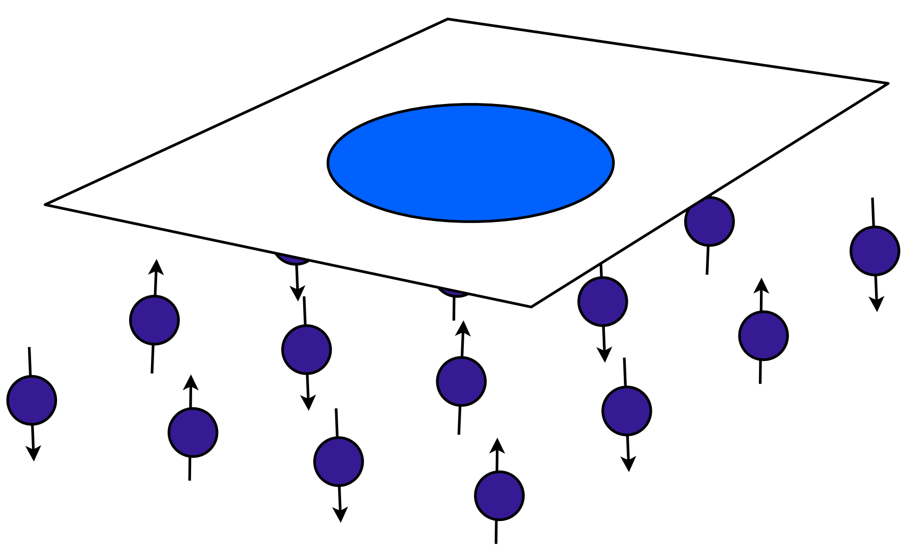

?

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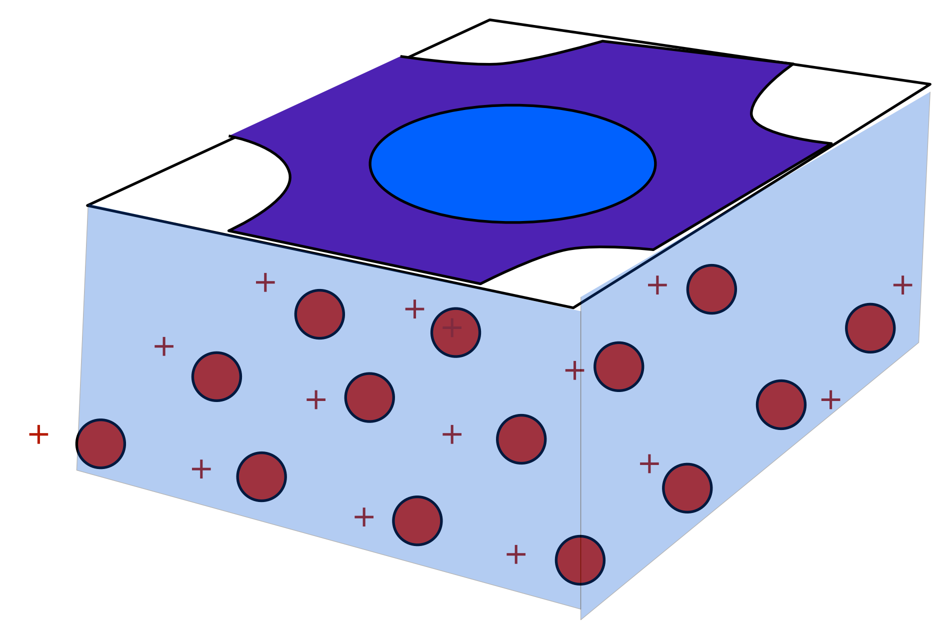
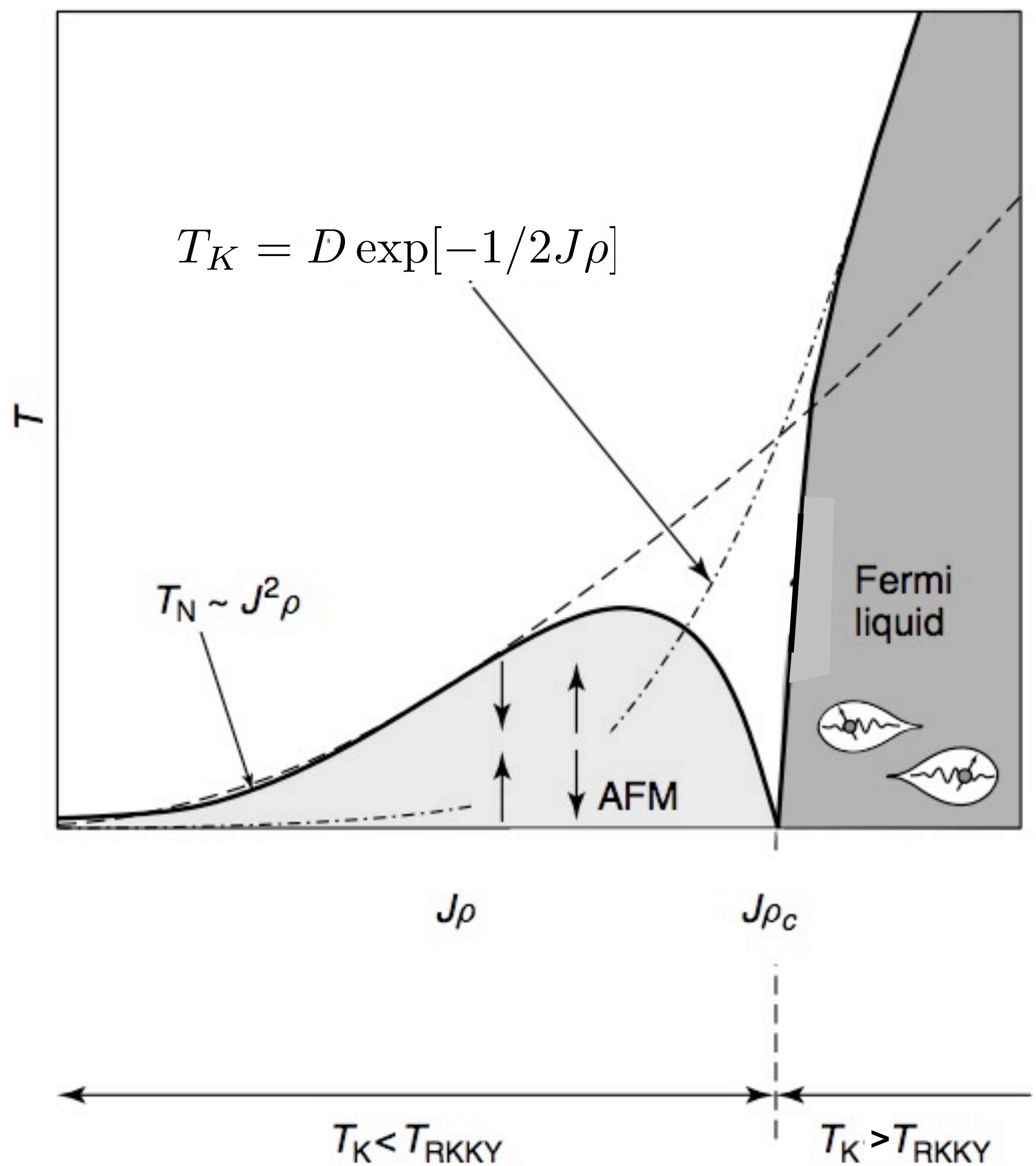
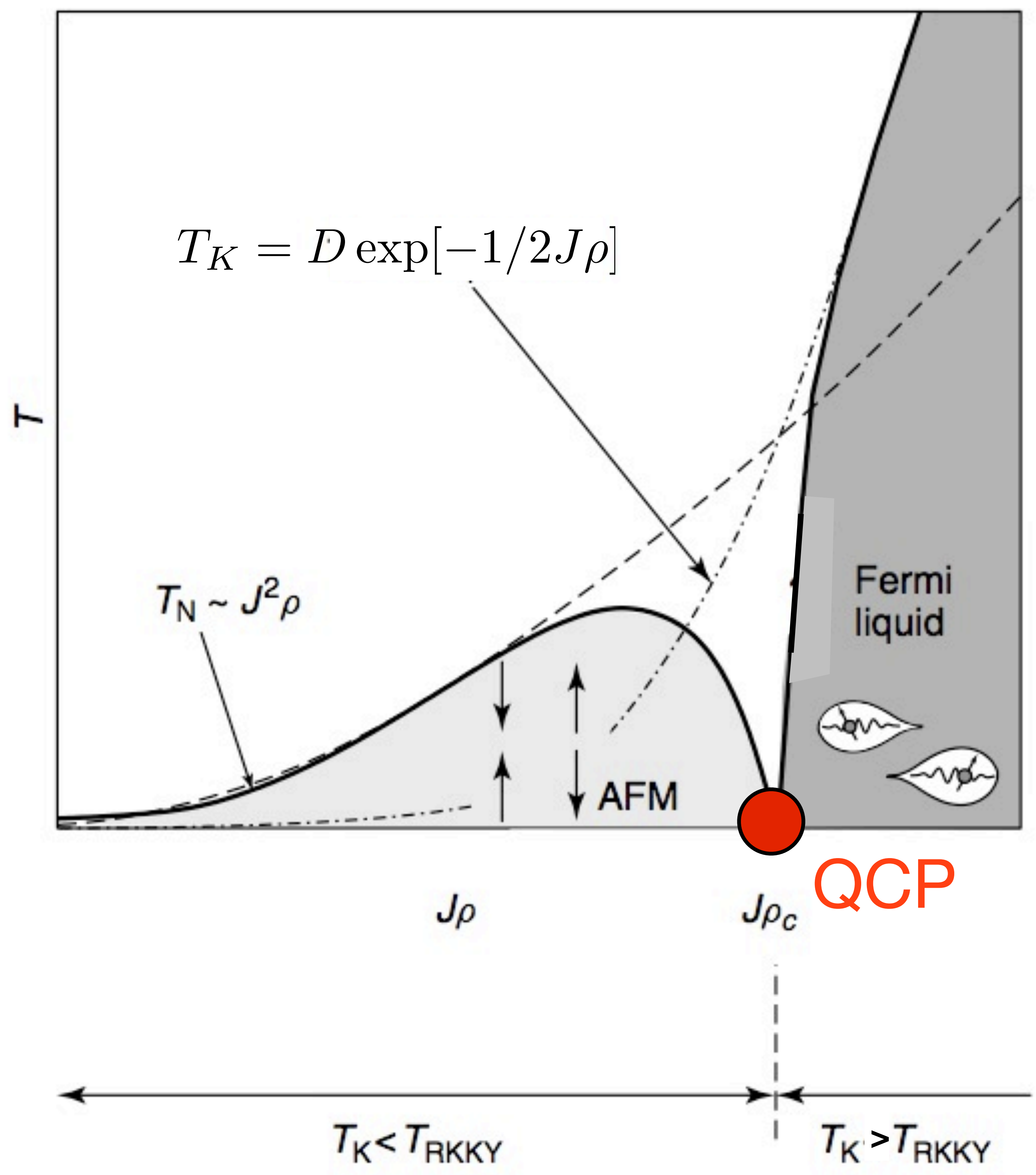




$T_K = D\exp[-1/2J\rho]$
T
$T_N \sim J^2\rho$
Fermi
liquid
AFM
$J\rho$
$J\rho_c$
$T_K < T_{RKKY}$
$T_K > T_{RKKY}$



$T_K = D\exp[-1/2J\rho]$
T
$T_N \sim J^2\rho$
Fermi liquid
AFM
QCP
$J\rho$
$J\rho_c$
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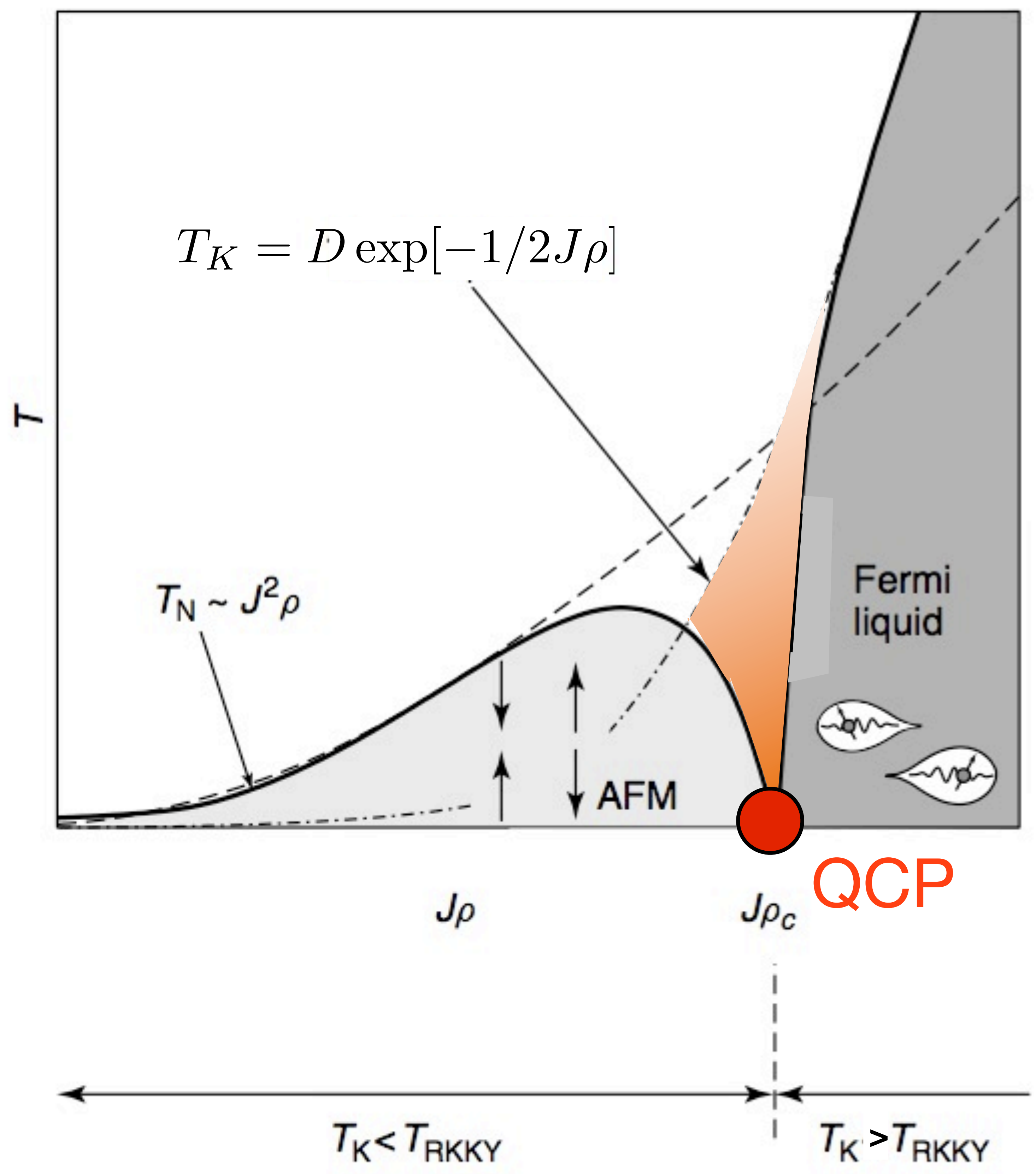
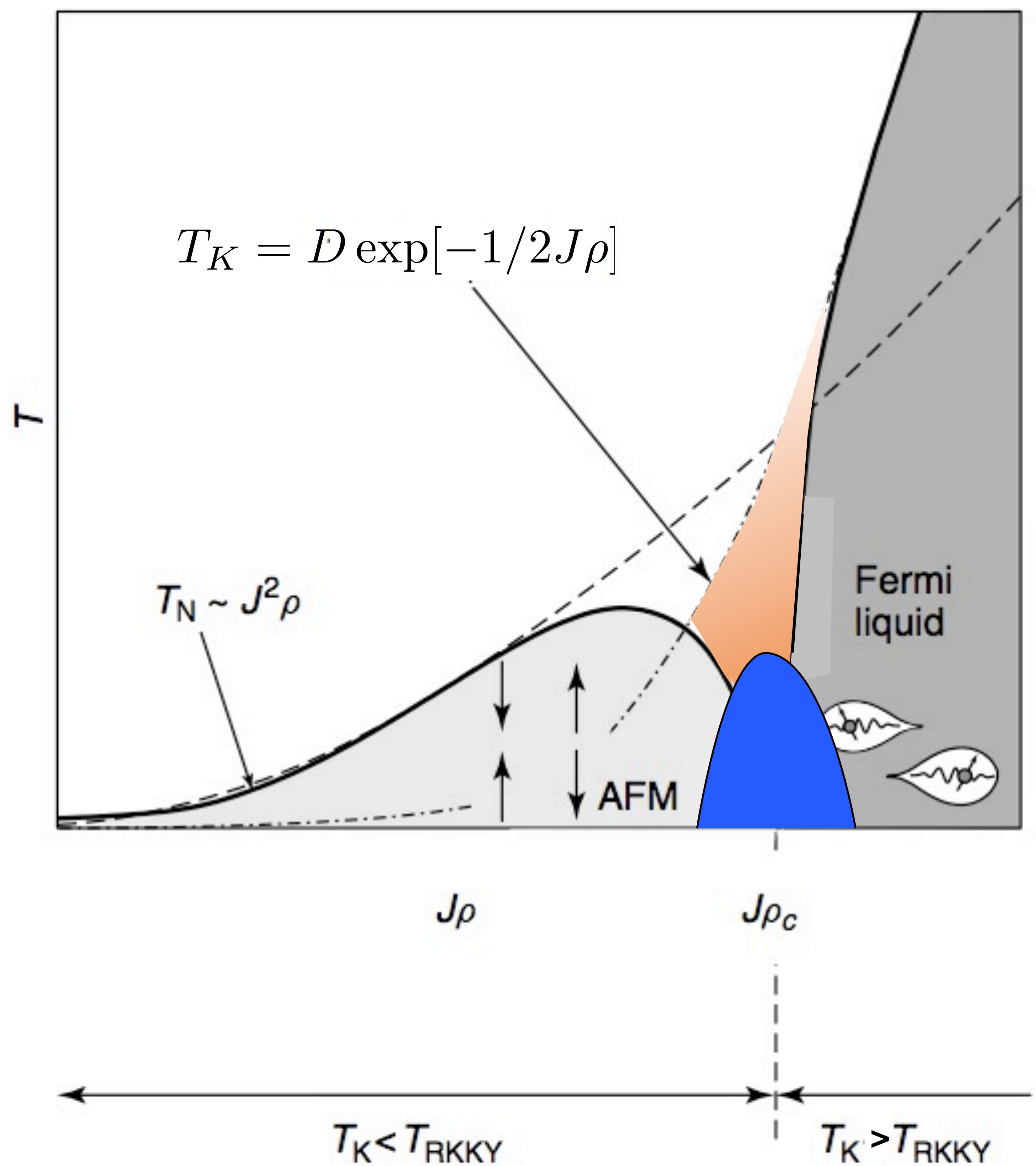


Strange Metal



Strange Metal

Novel Phases
(SC, Hidden order)

A new era of mysteries.

•Introduction - the **d-f** connection, heavy fermion primer.

A new era of mysteries:

- Quantum Criticality

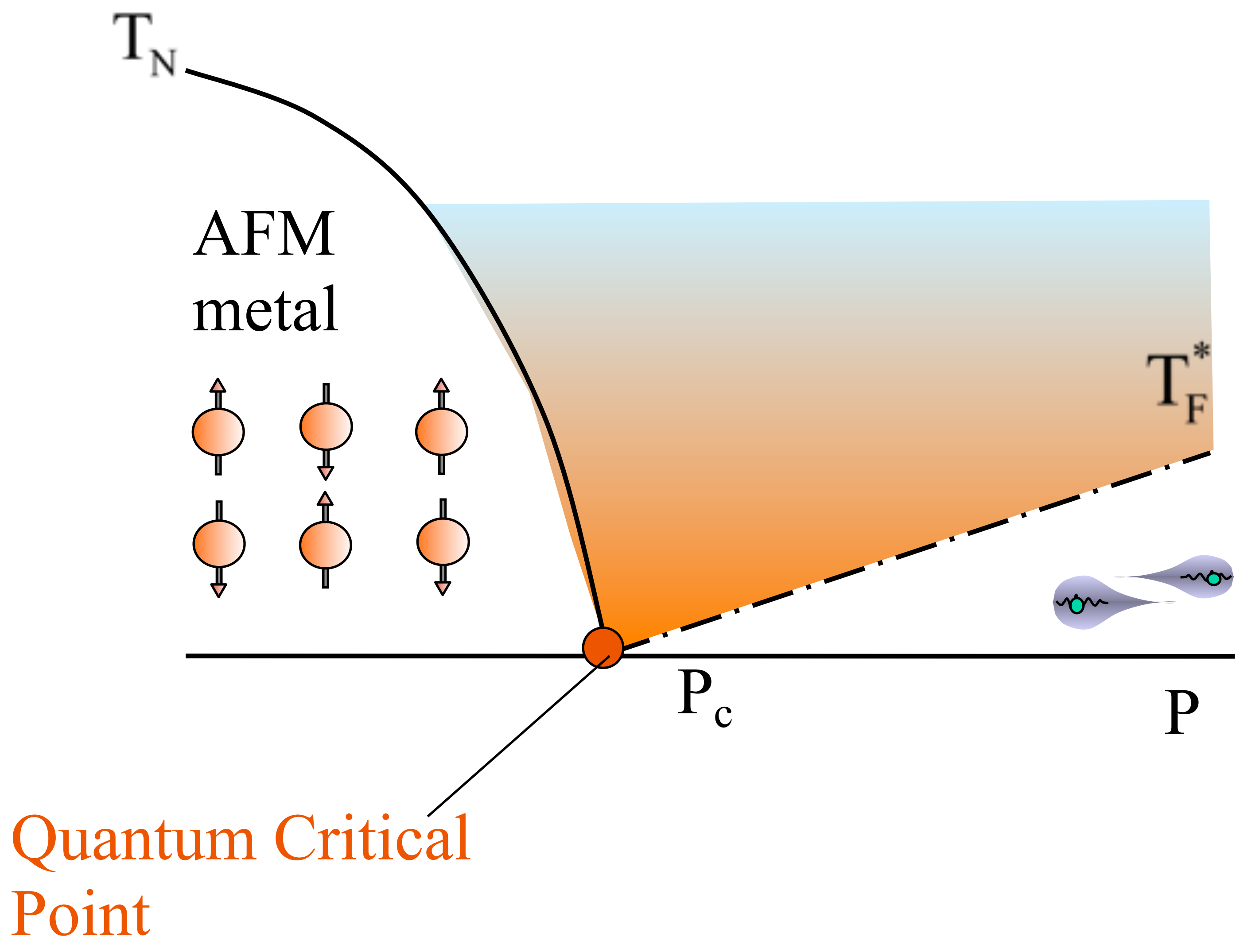
- Spin in (heavy fermion) superconductivity

- Hidden order in URu_2Si_2

- Vortex model for intrinsically quantum critical $YbAlB_4$.

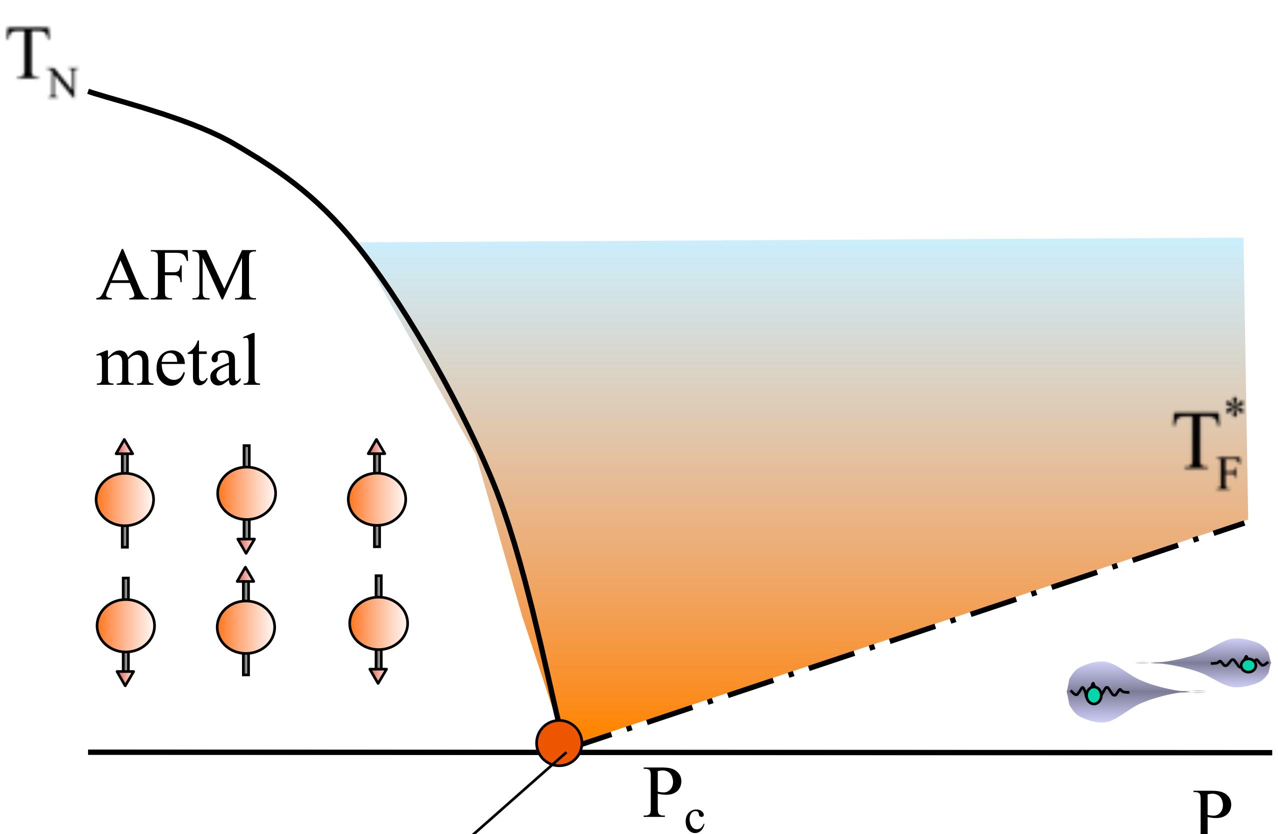
Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



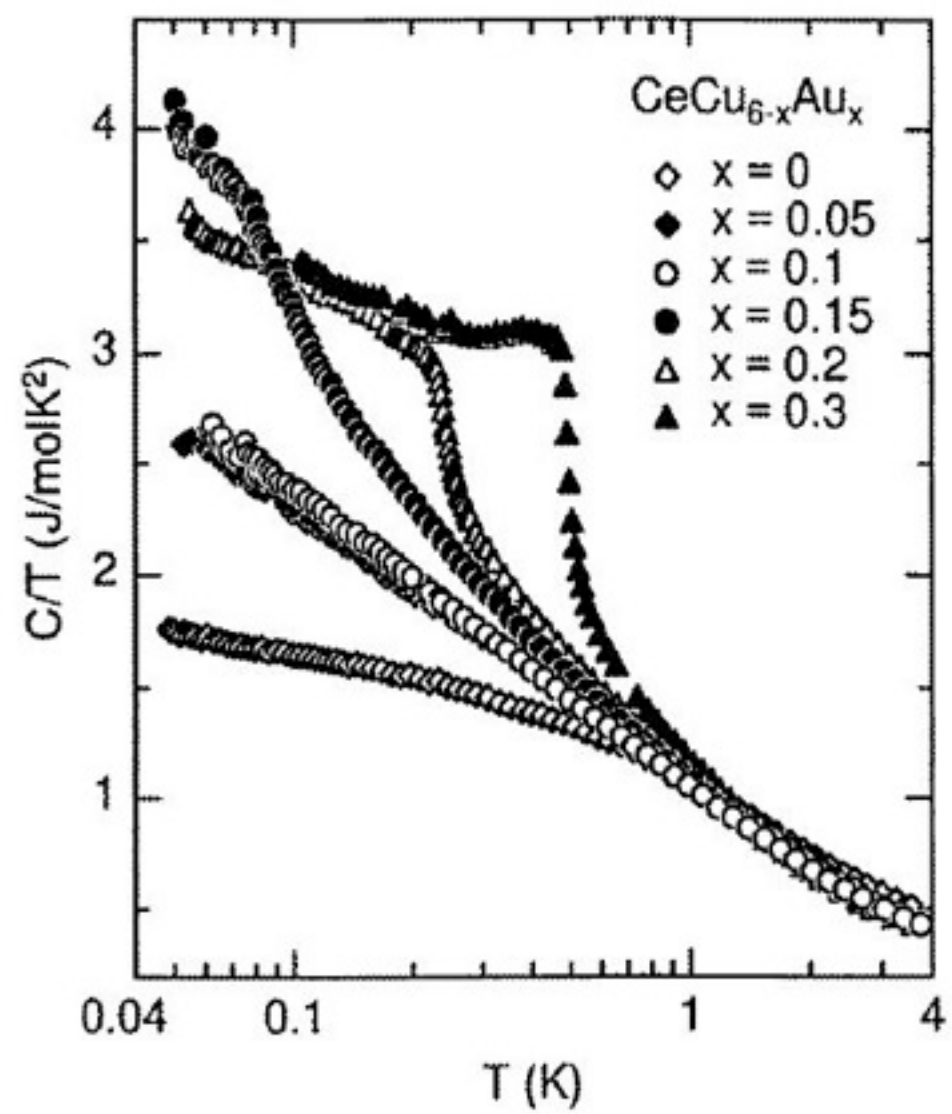
Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials

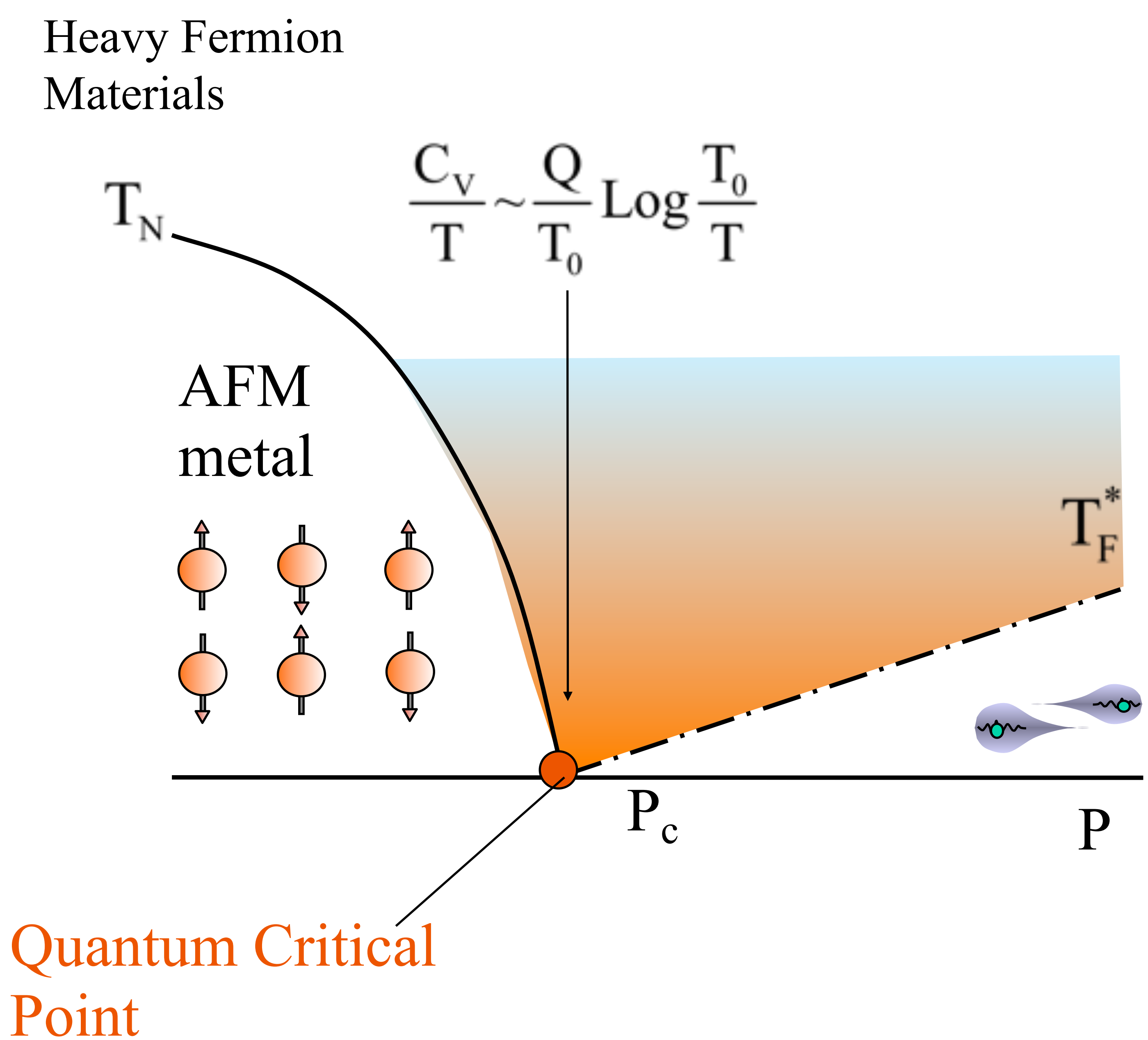


Quantum Critical Point

H. Von Lohneyson (1996)



Quantum Criticality: divergent specific heat capacity



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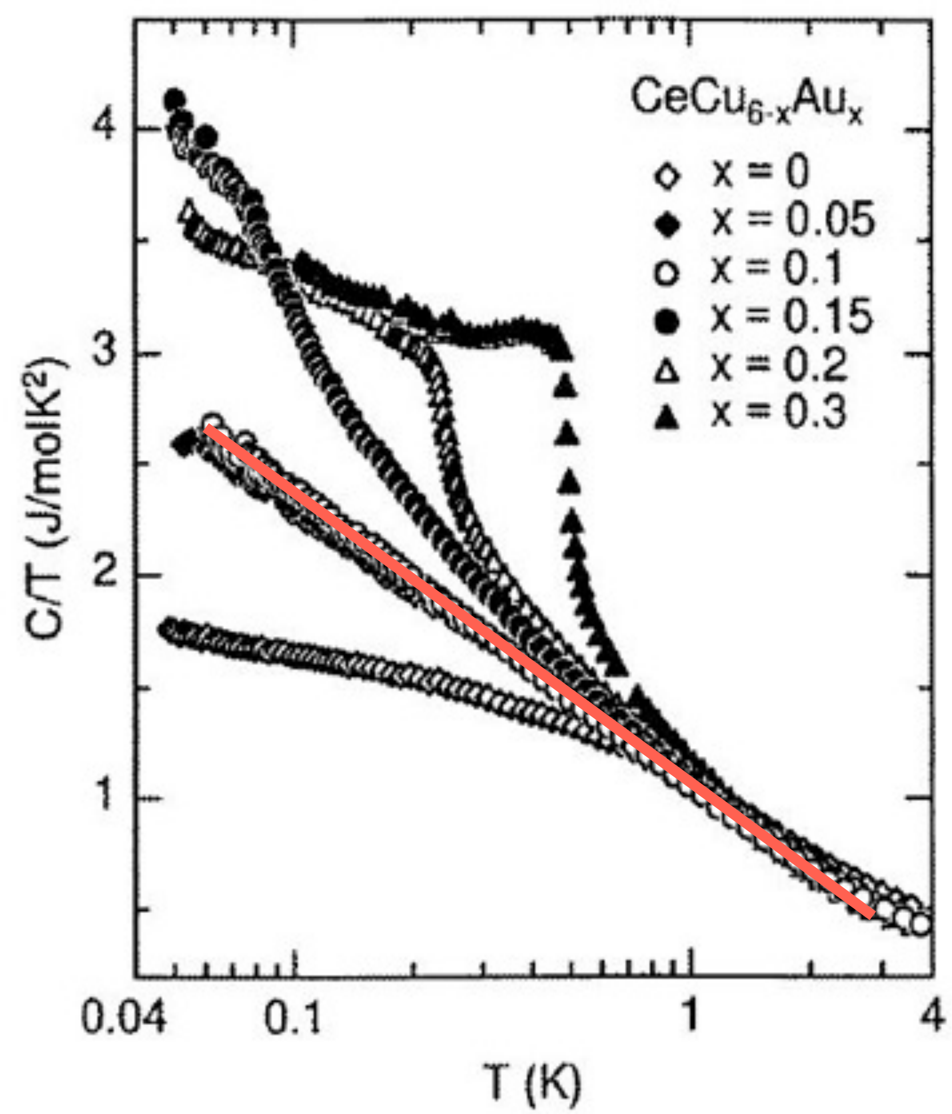
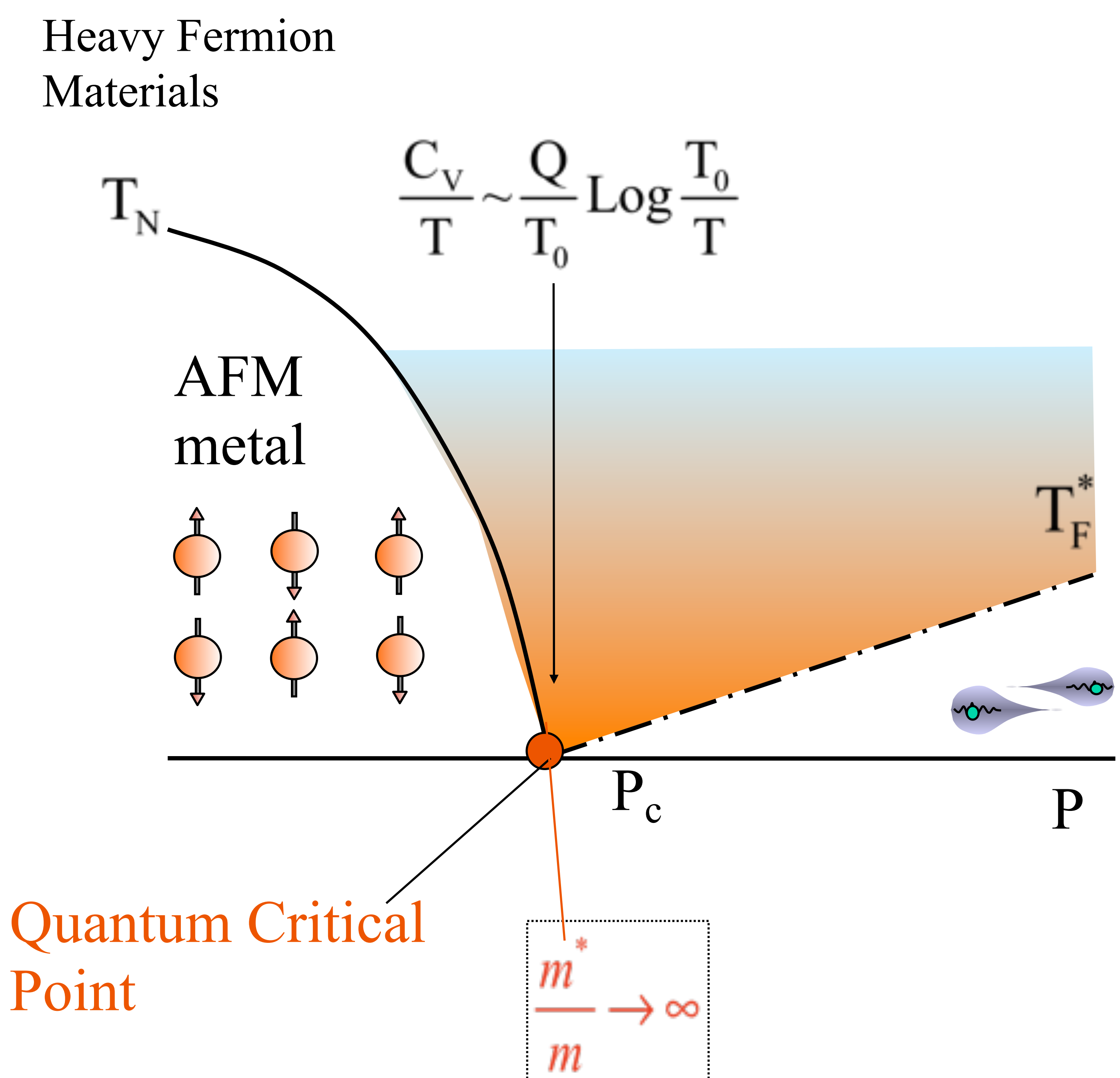


Quantum Criticality: divergent specific heat capacity



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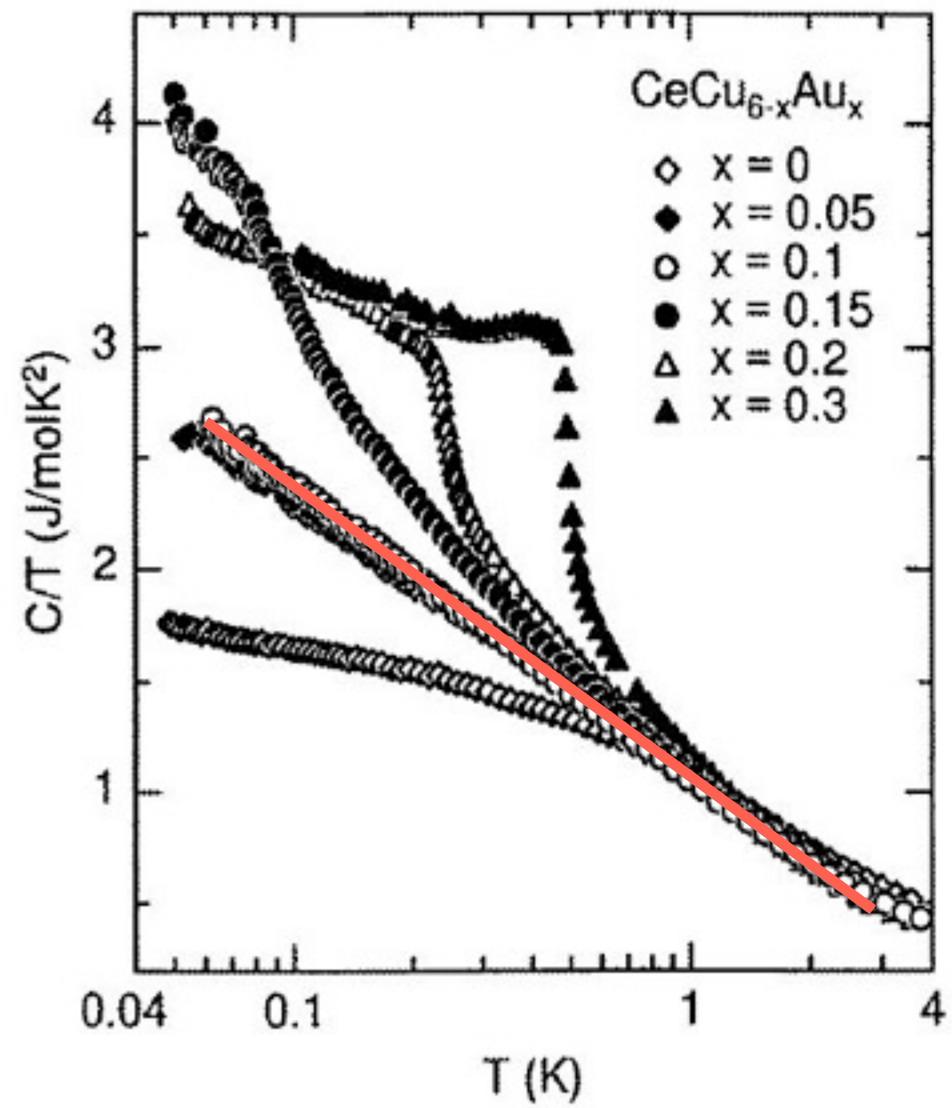
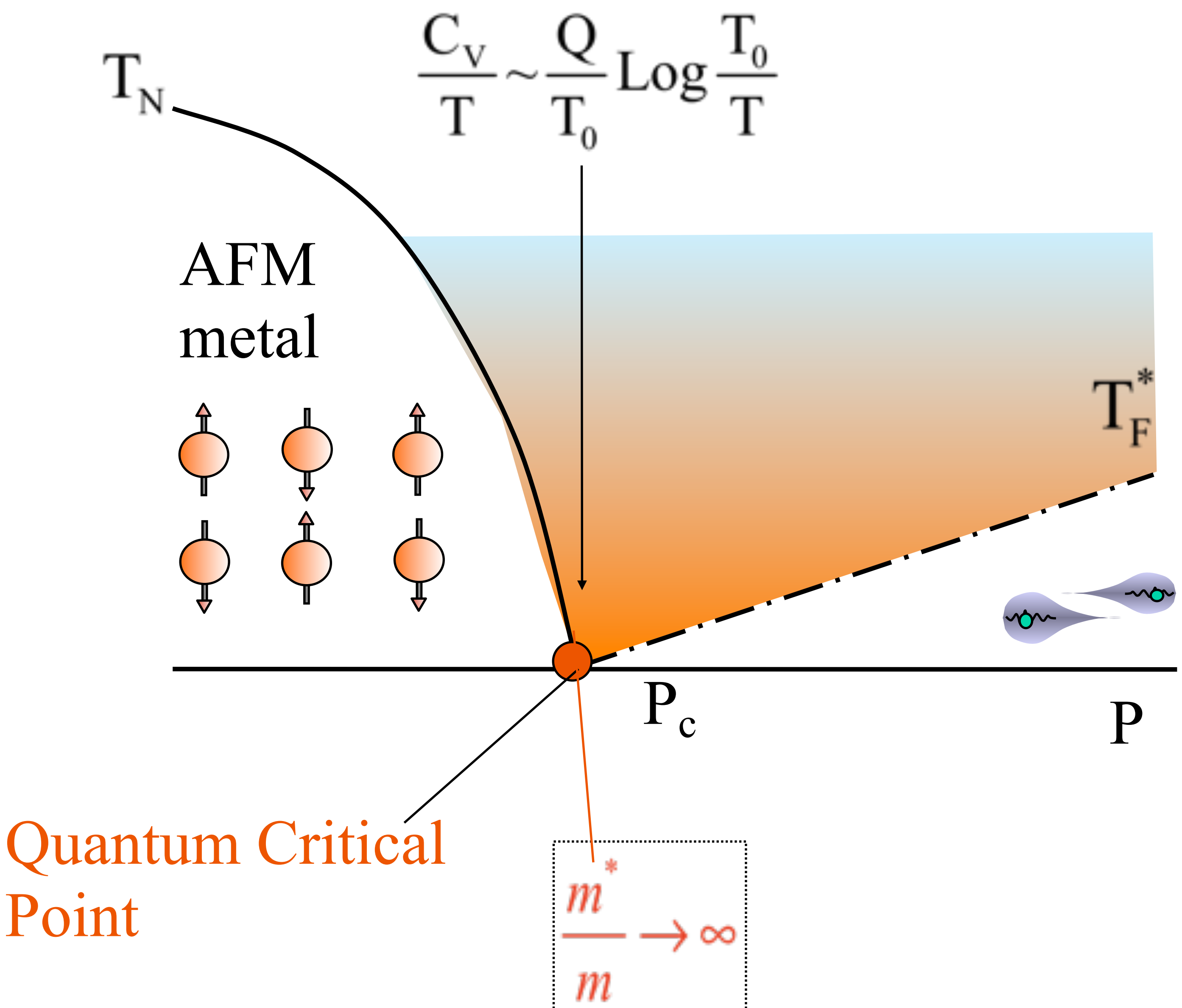


Quantum Criticality: divergent specific heat capacity

Heavy Fermion Materials



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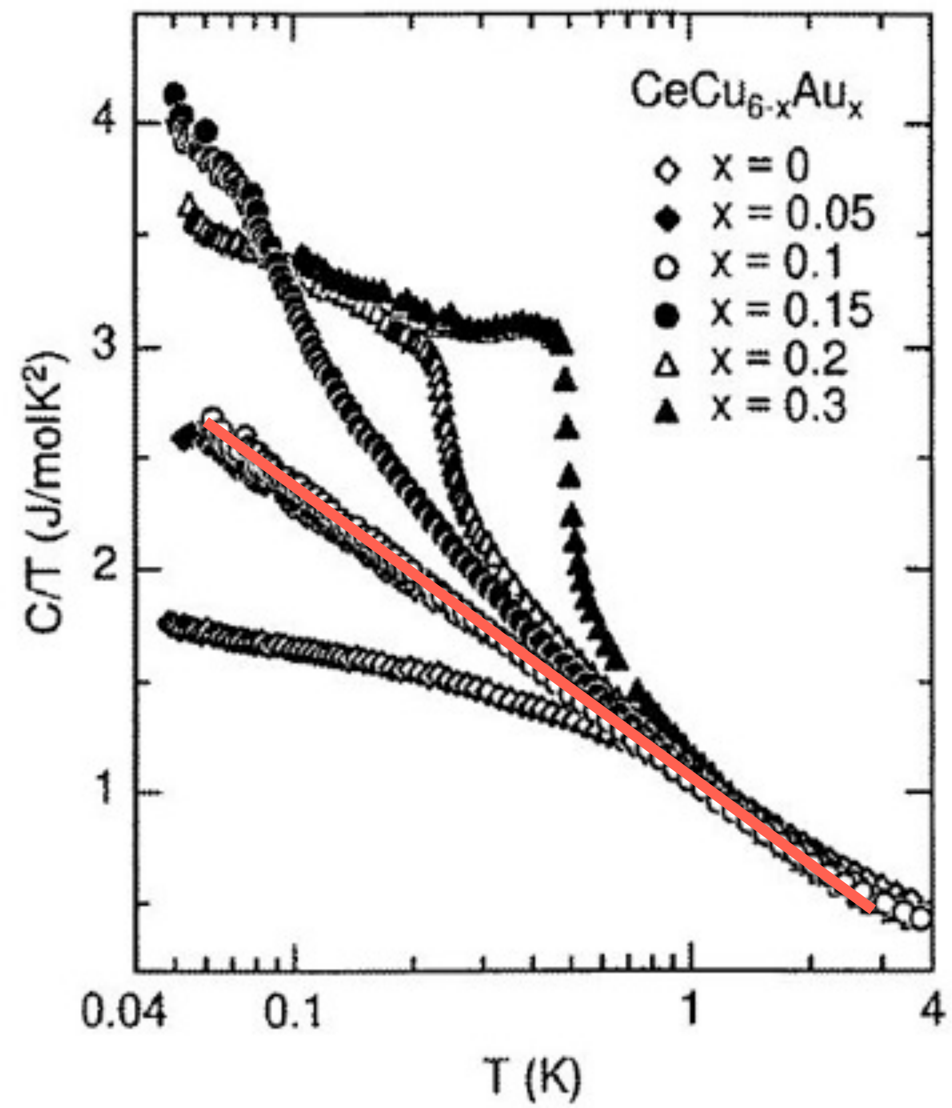
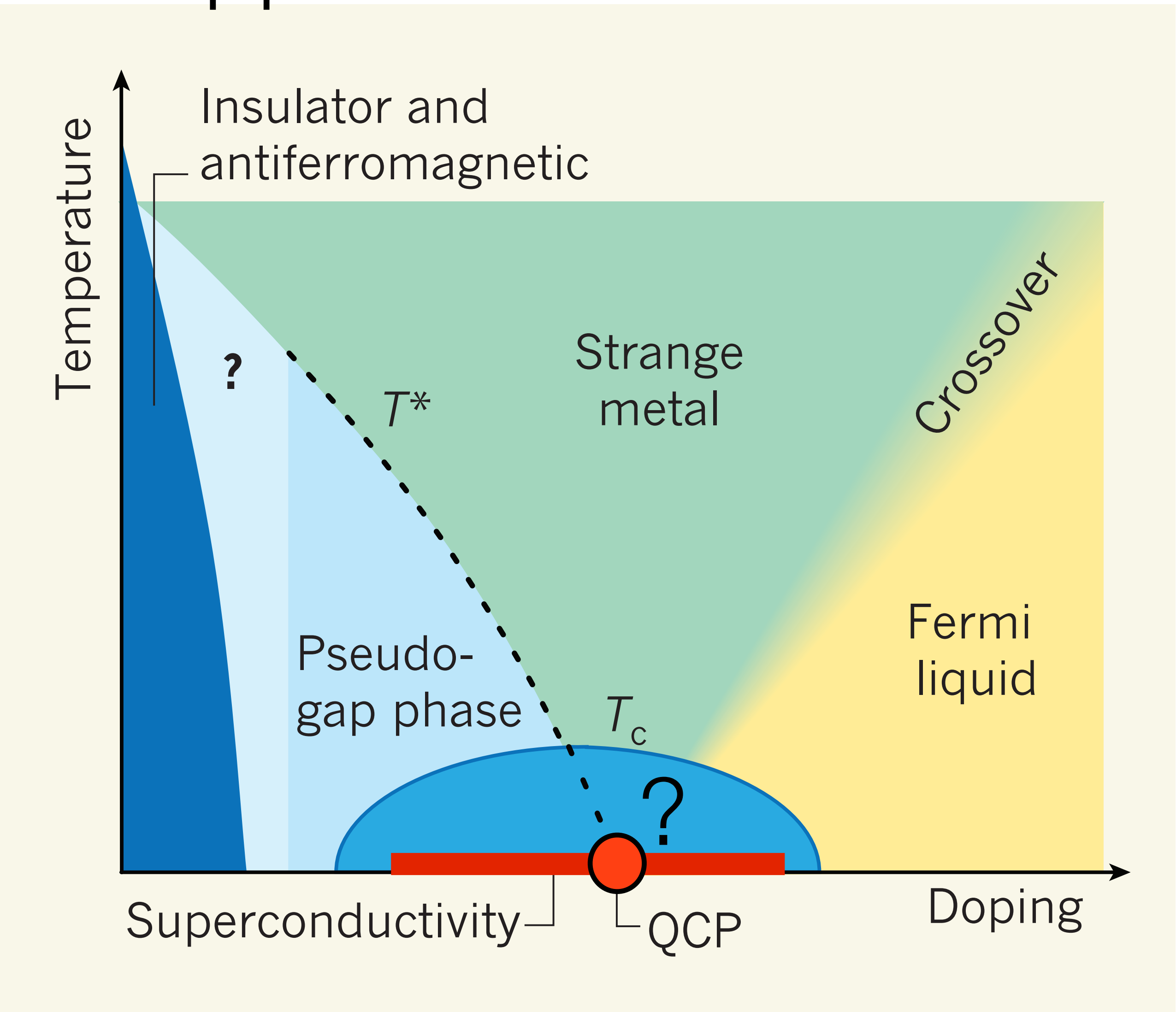


Break-down of Landau Fermi liquid

What lies beneath the dome?

Copper based SC



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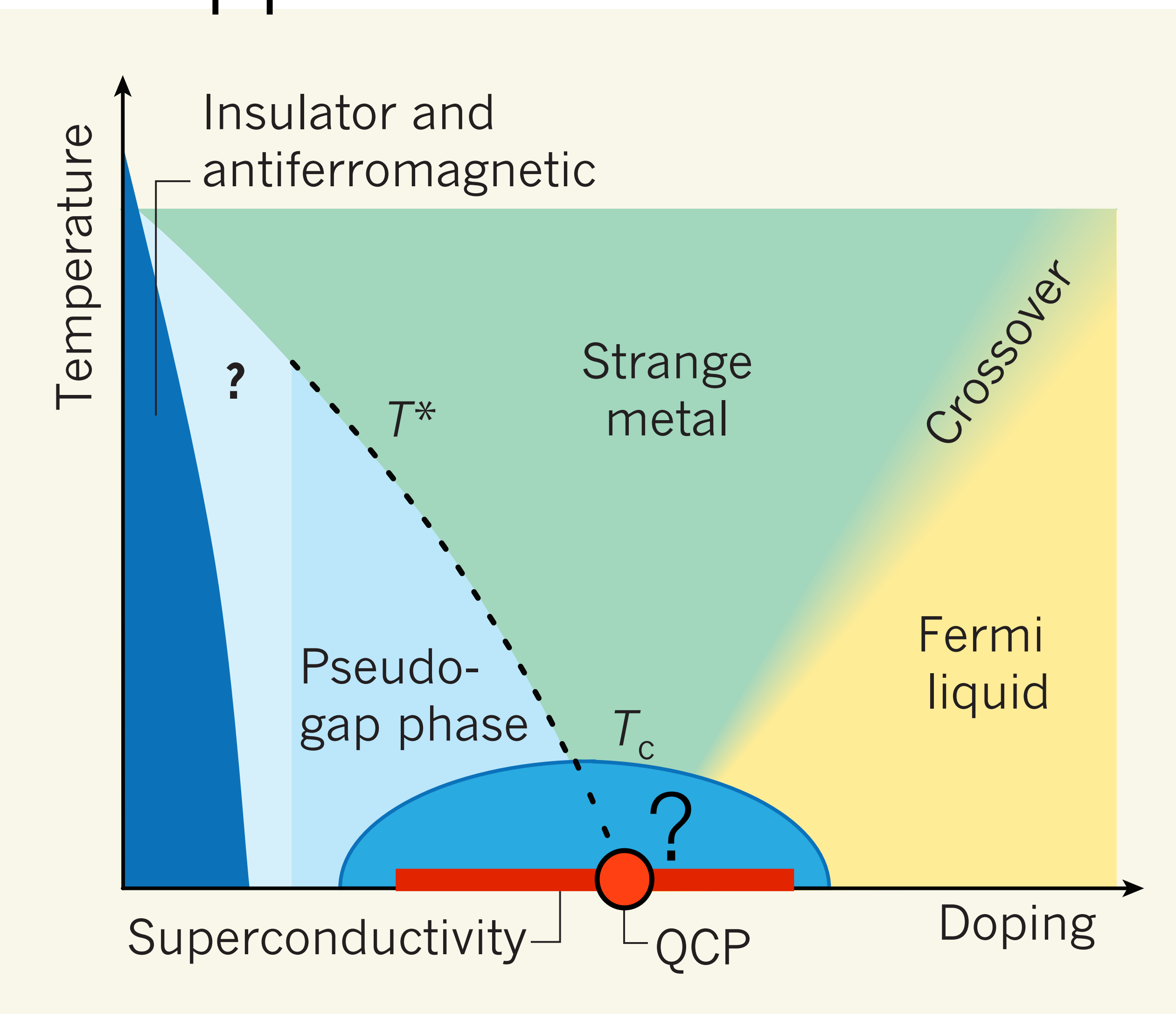
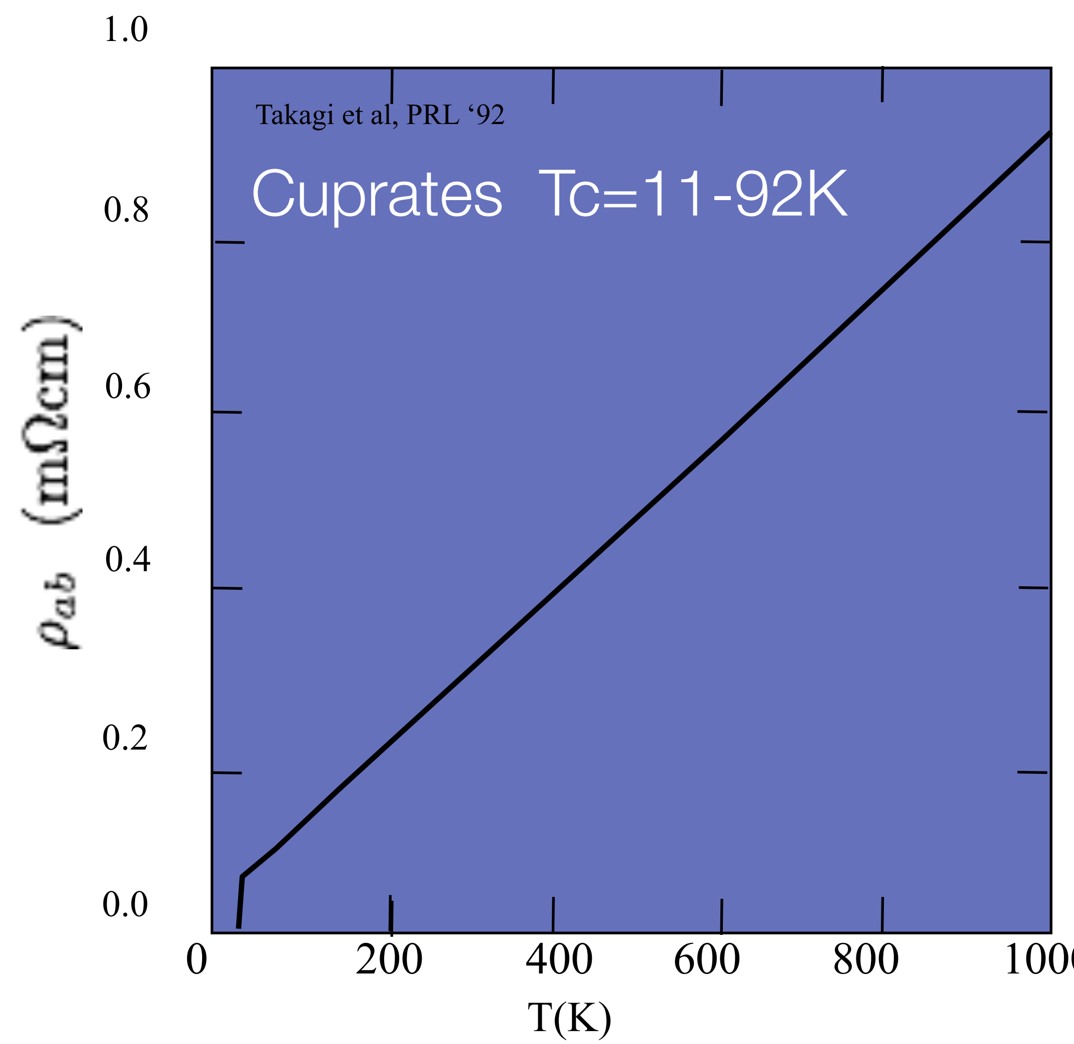
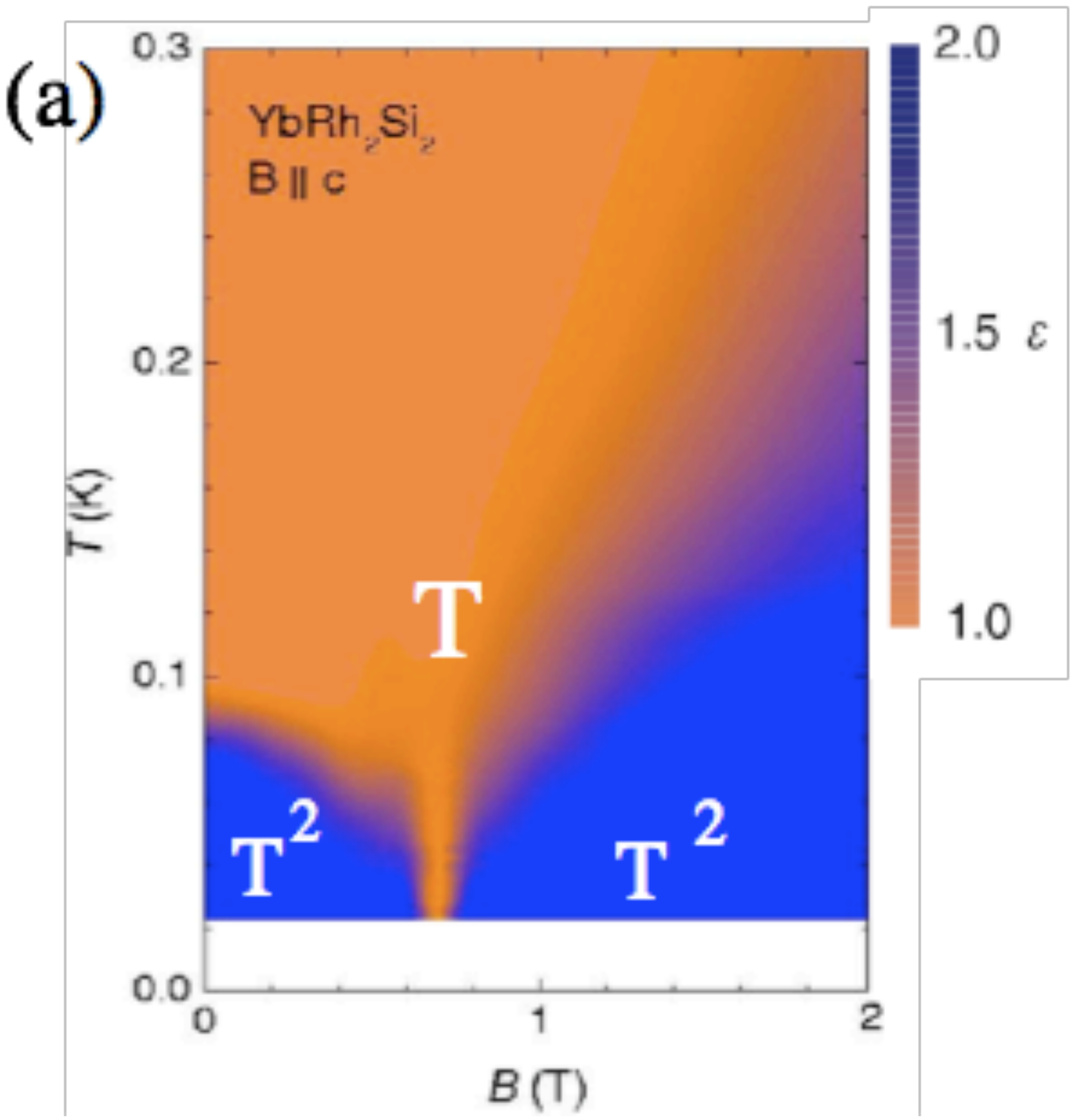




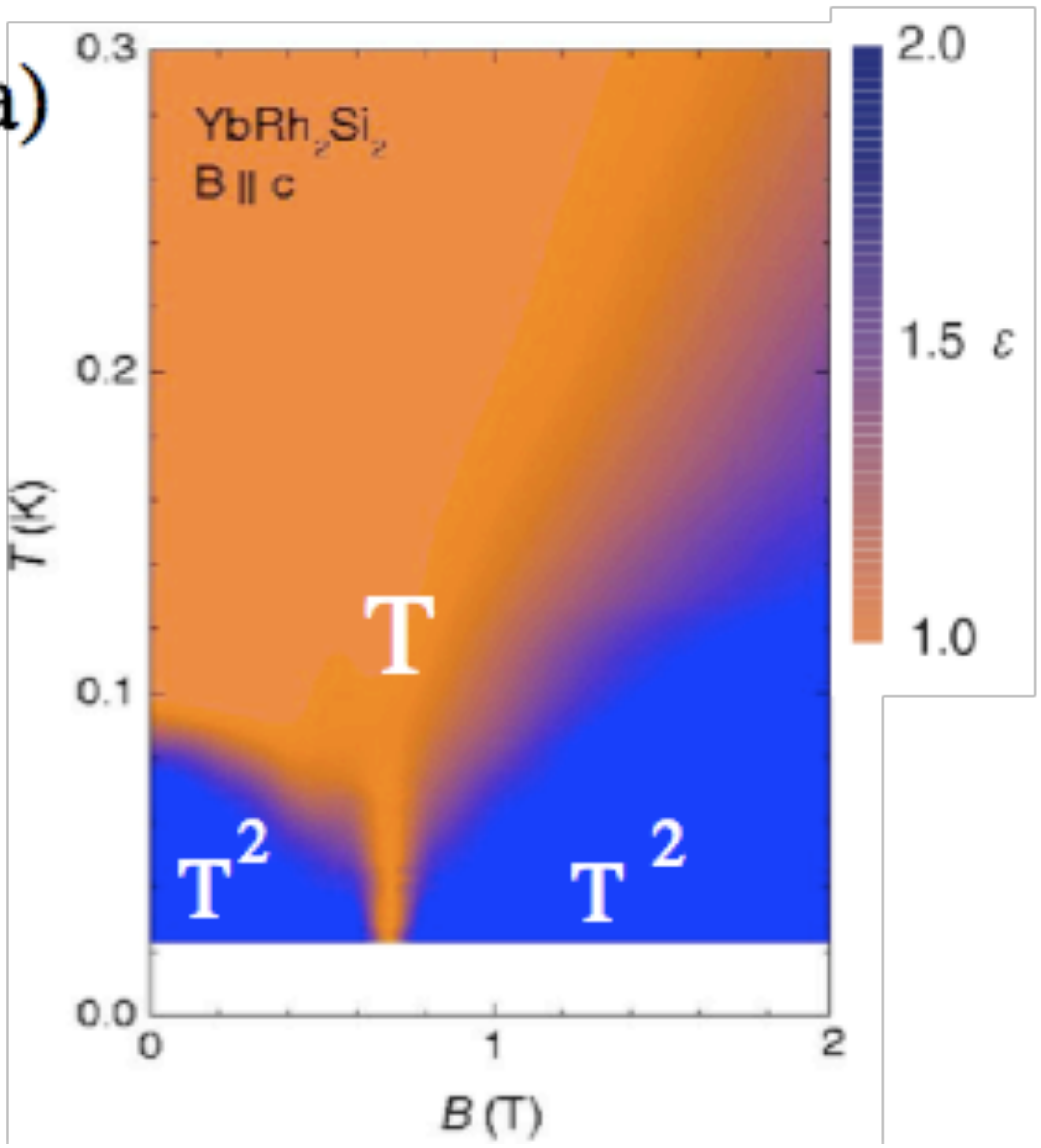
$YbRh_2Si_2$: Field tuned quantum criticality.



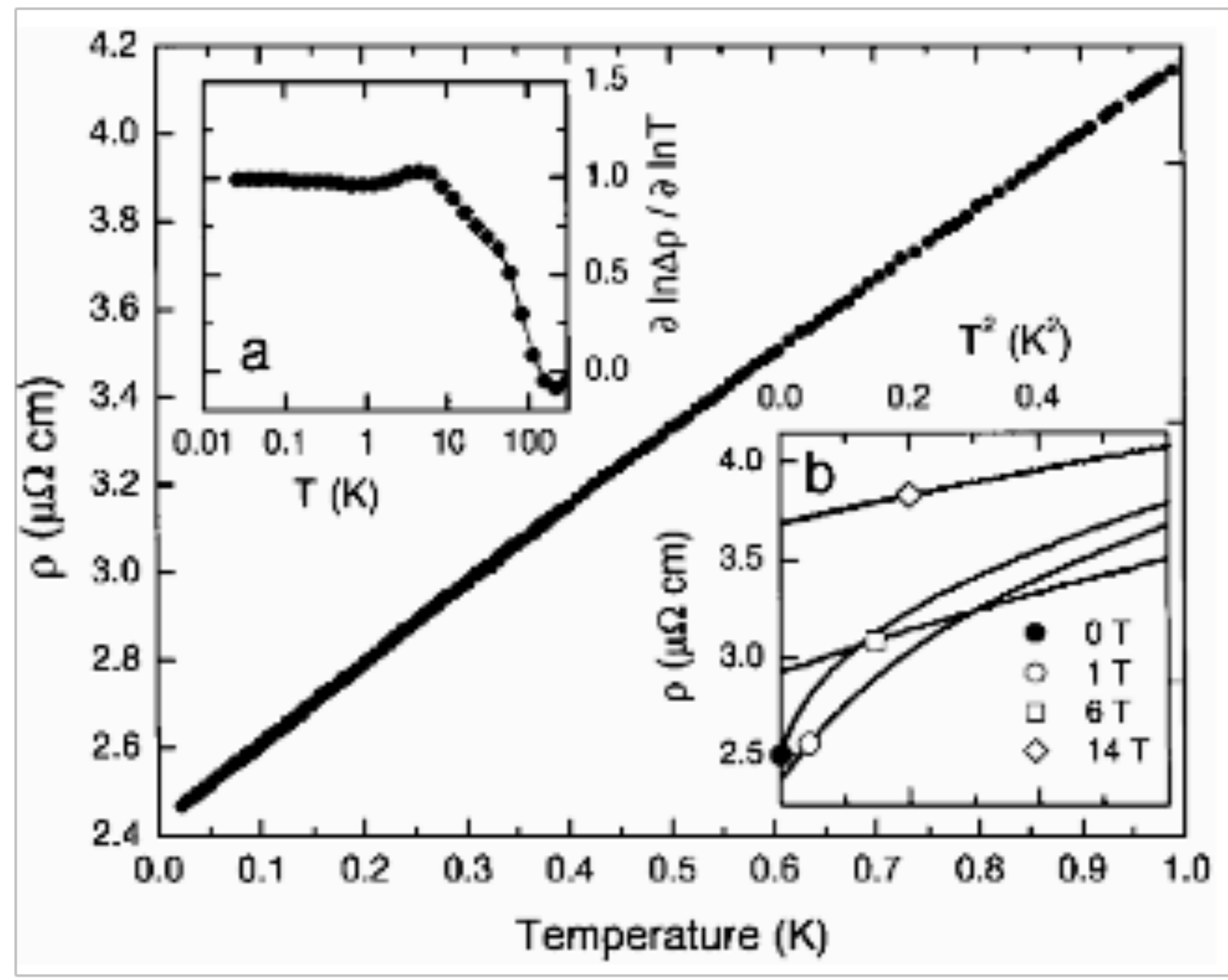
Custers et al, (2003)

YbRh$_2$Si$_2$: Field tuned quantum criticality.

(a)



(b)



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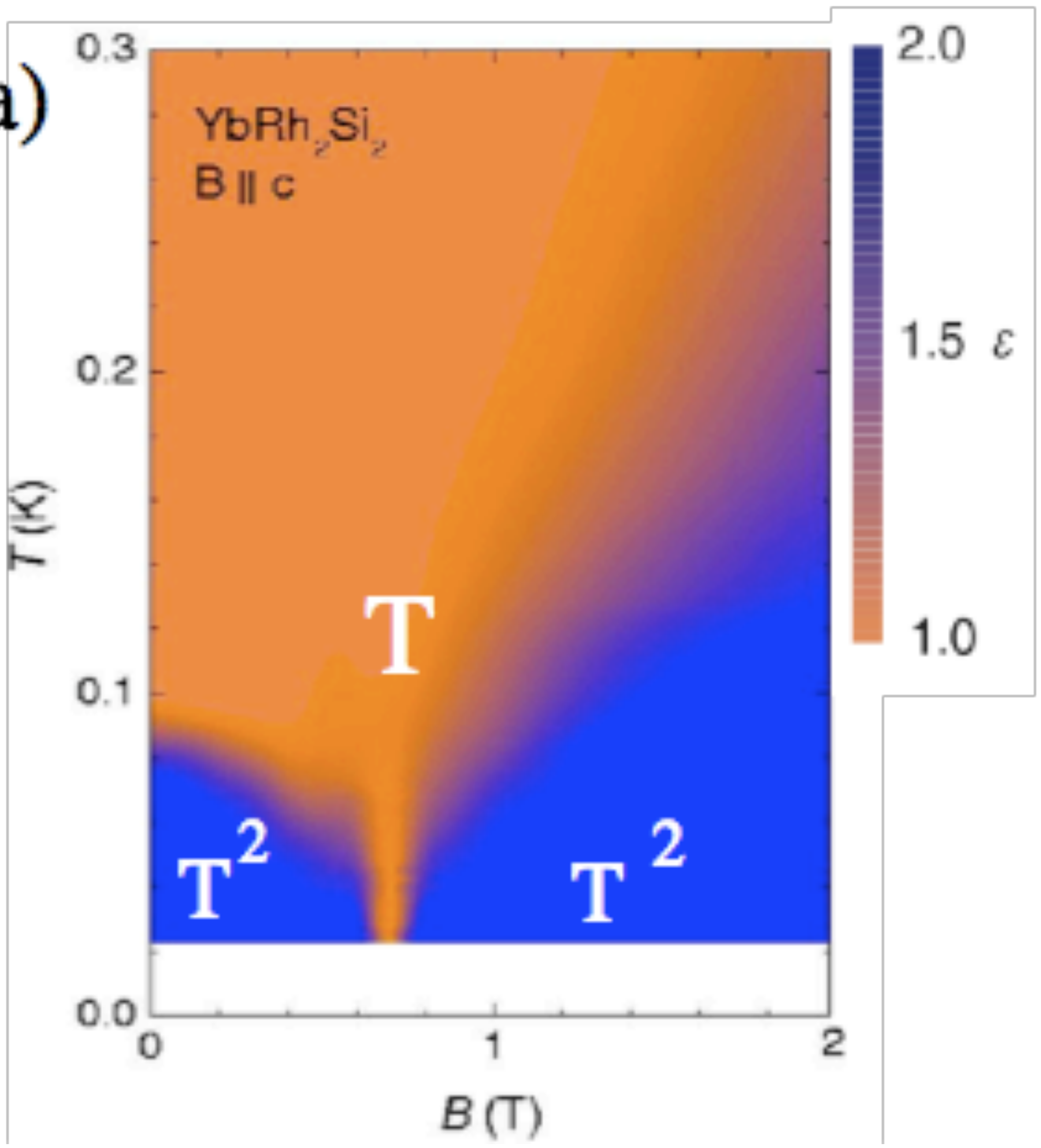

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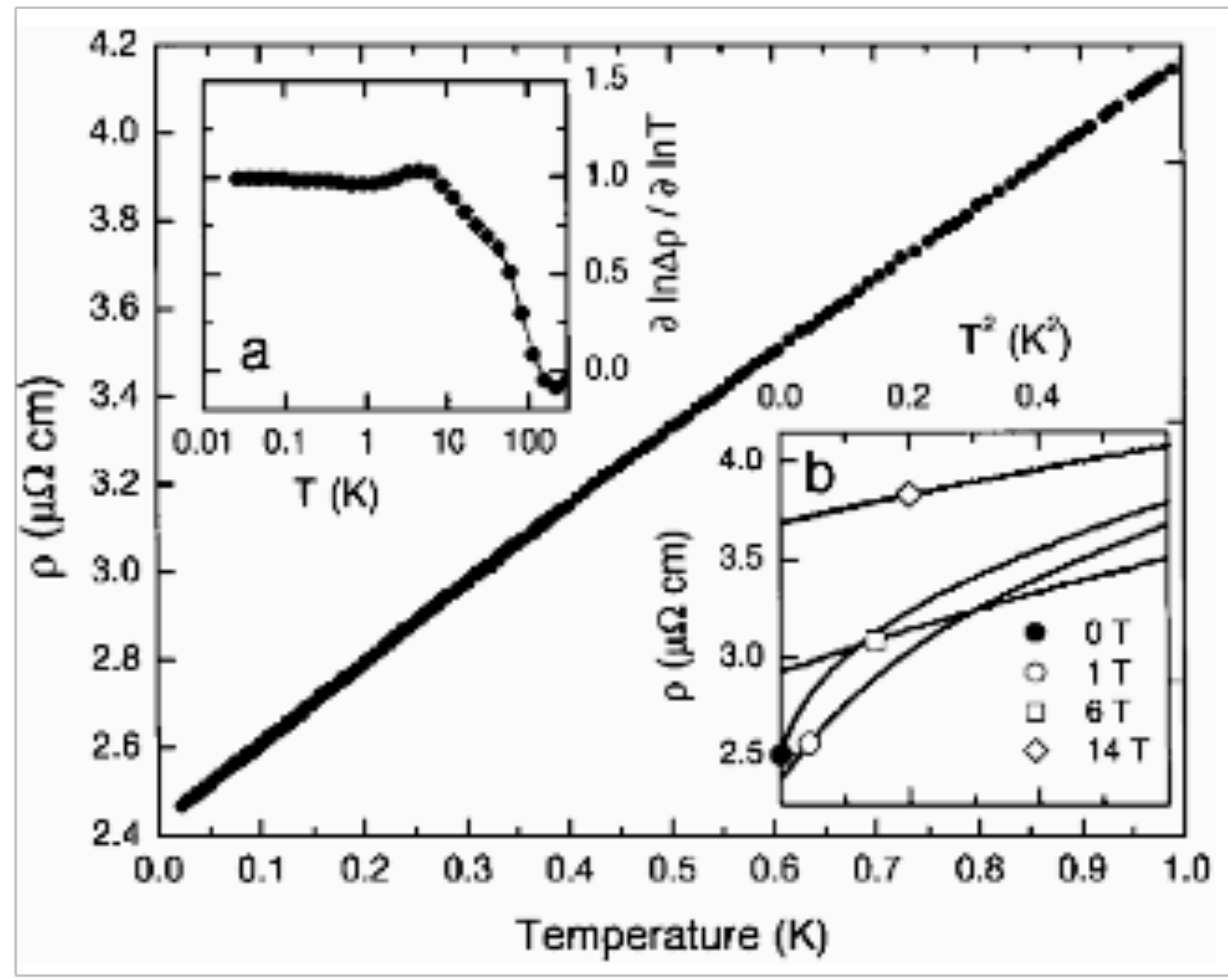

Reminiscent of cuprate sc at optimal doping.

Custers et al, (2003)

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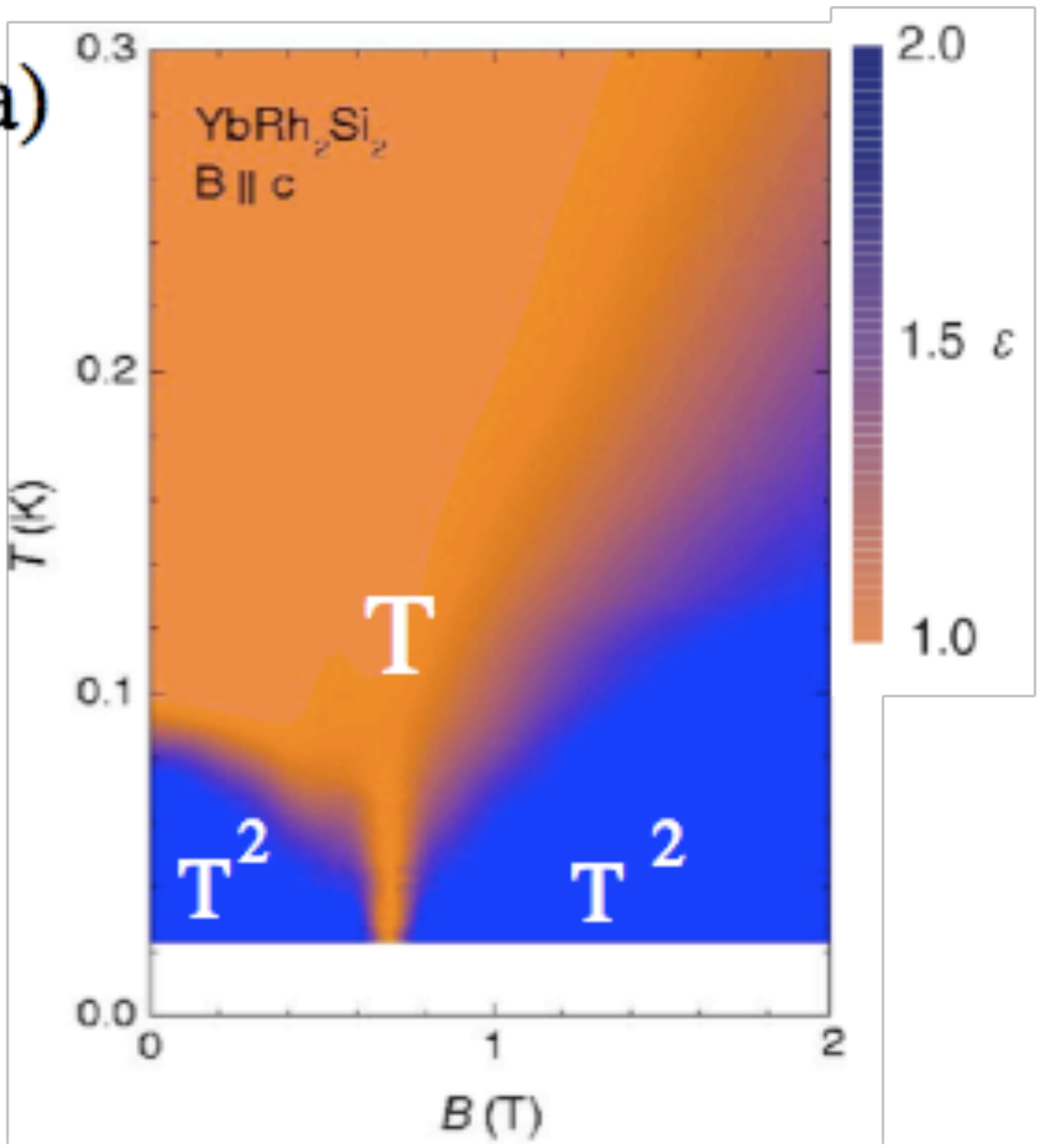

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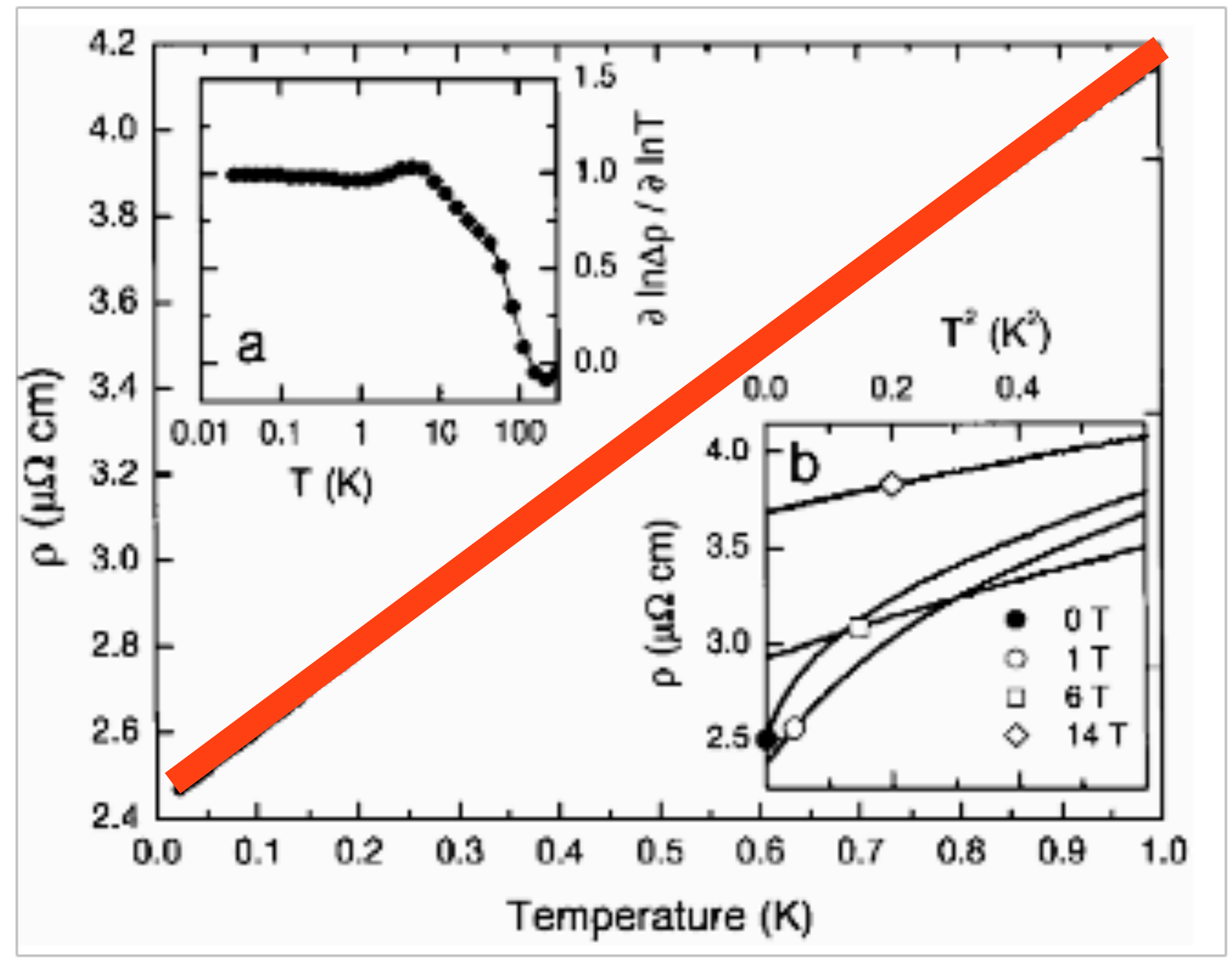
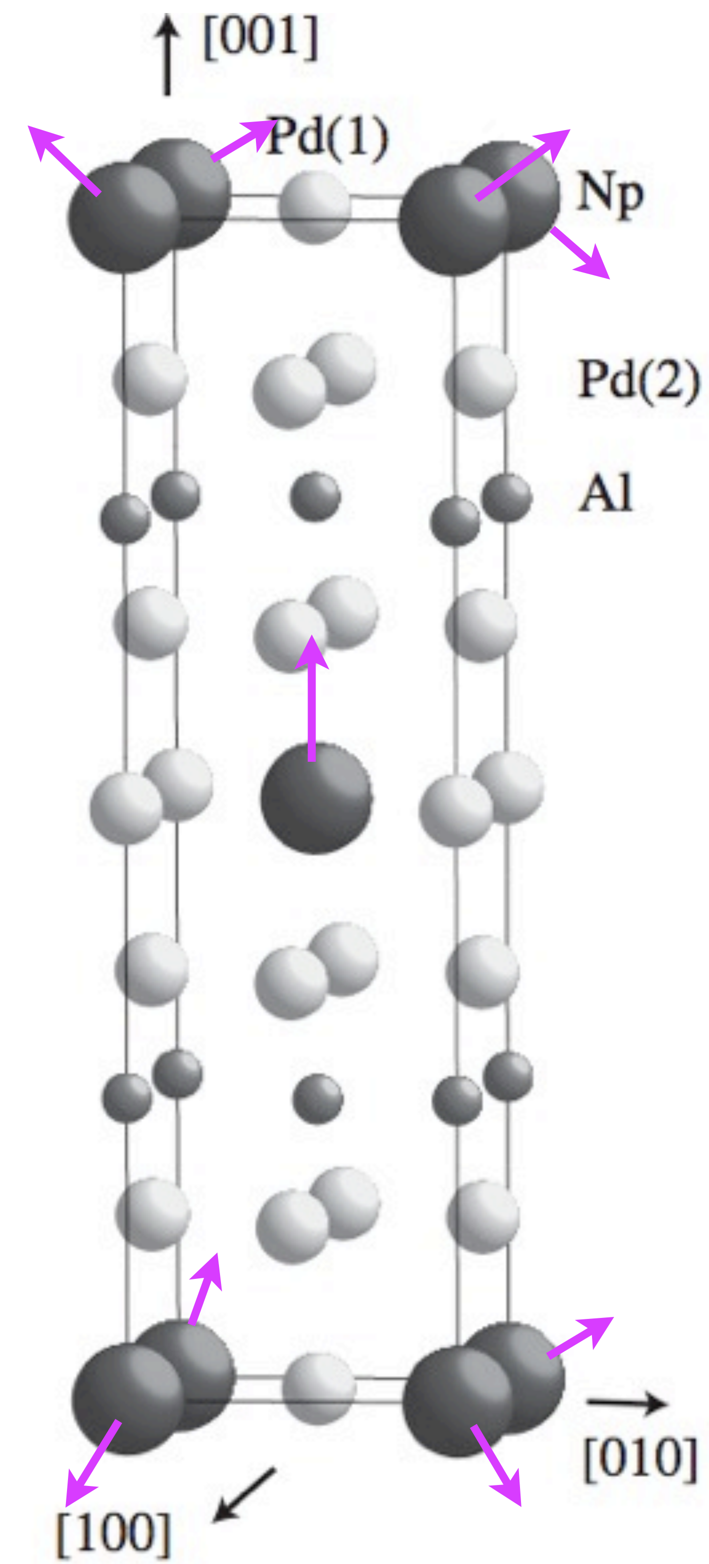


Custers et al, (2003)

Reminiscent of cuprate sc at optimal doping.

What is the nature of the quantum criticality and the strange metal?

$NpPd_5Al_2$ (cf $CeCoIn_5$): Curie HFSC

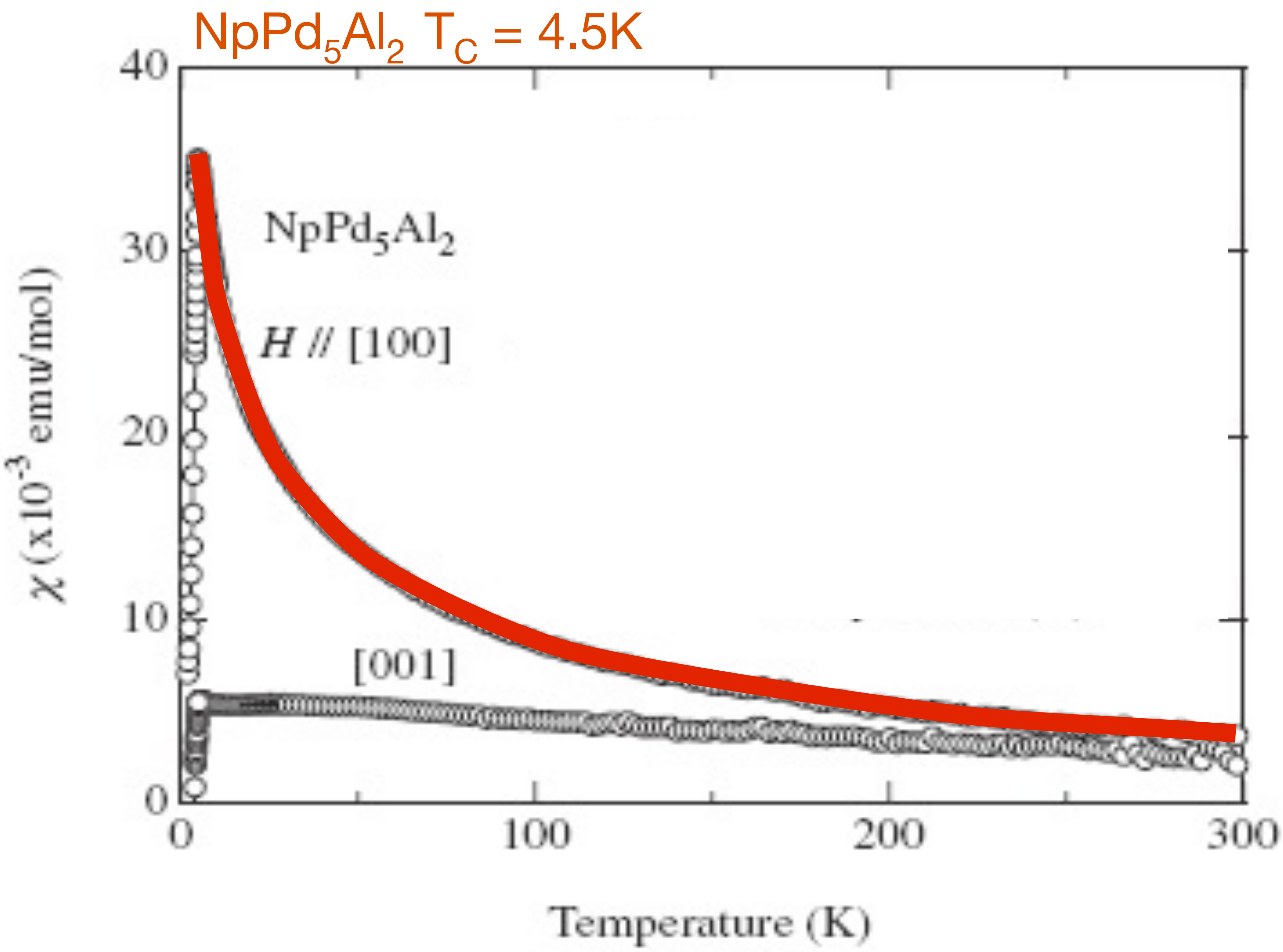


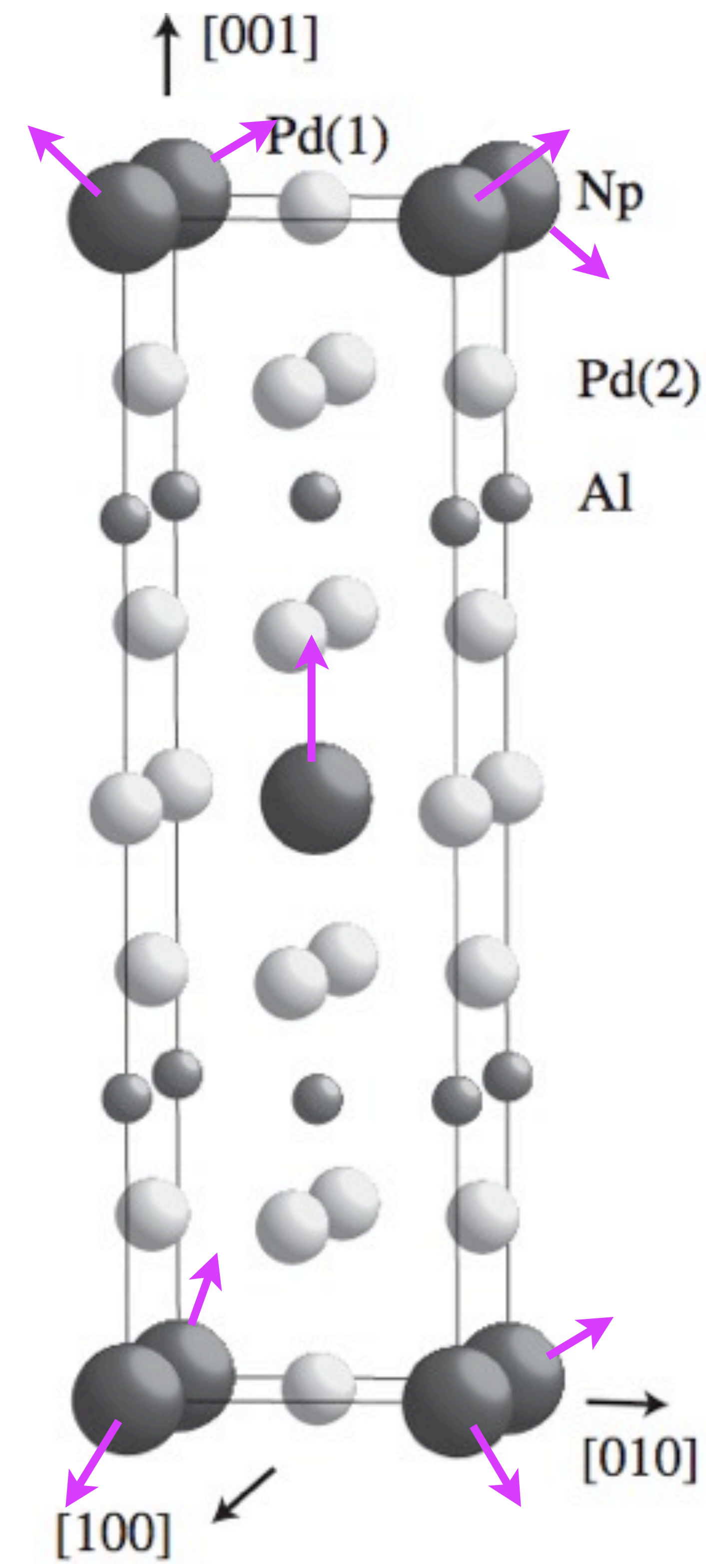
4.5K Heavy Fermion S.C

$NpAl_2Pd_5$

Aoki et al 2007

$NpPd_5Al_2$ (cf $CeCoIn_5$): Curie HFSC





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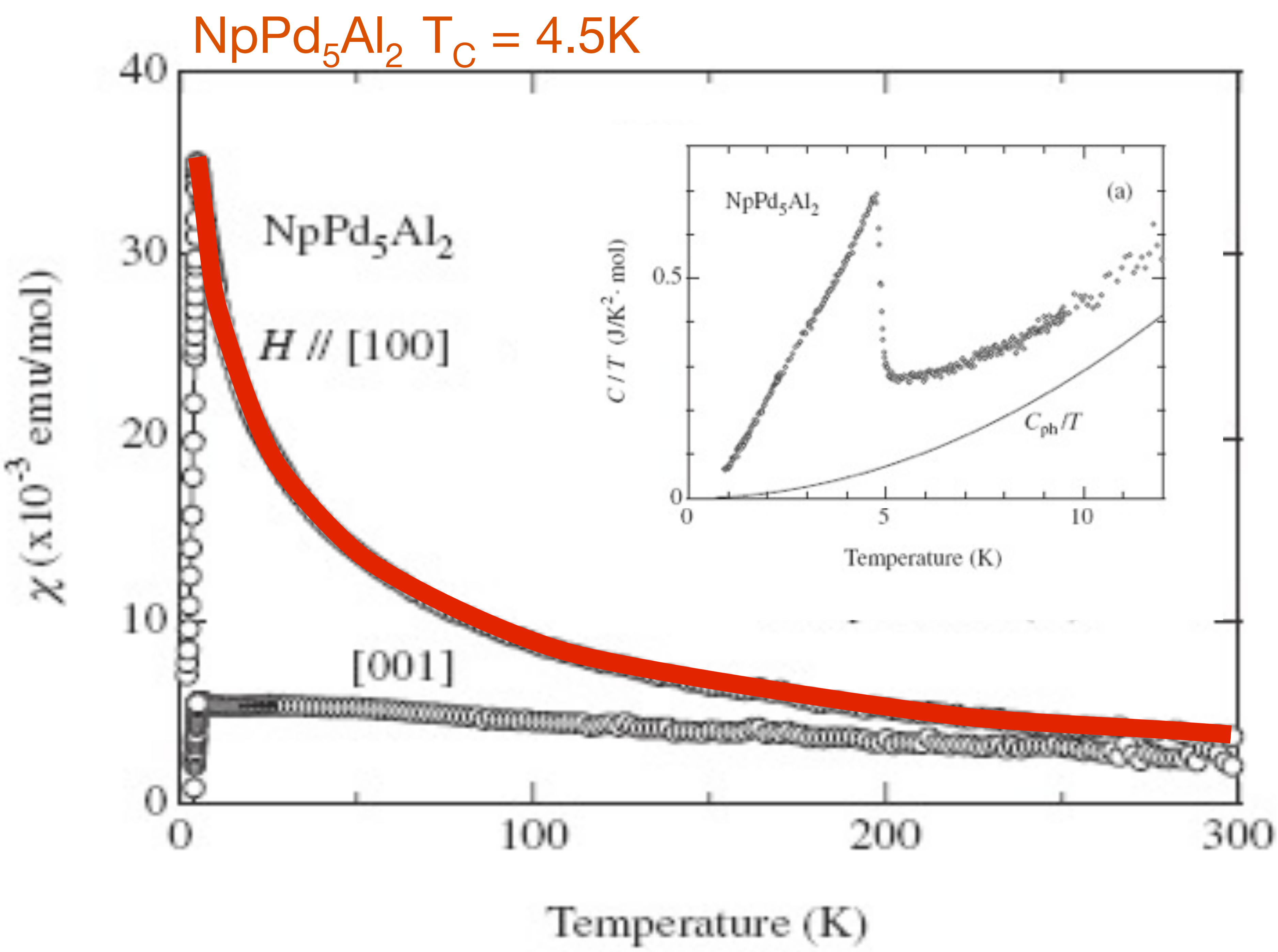

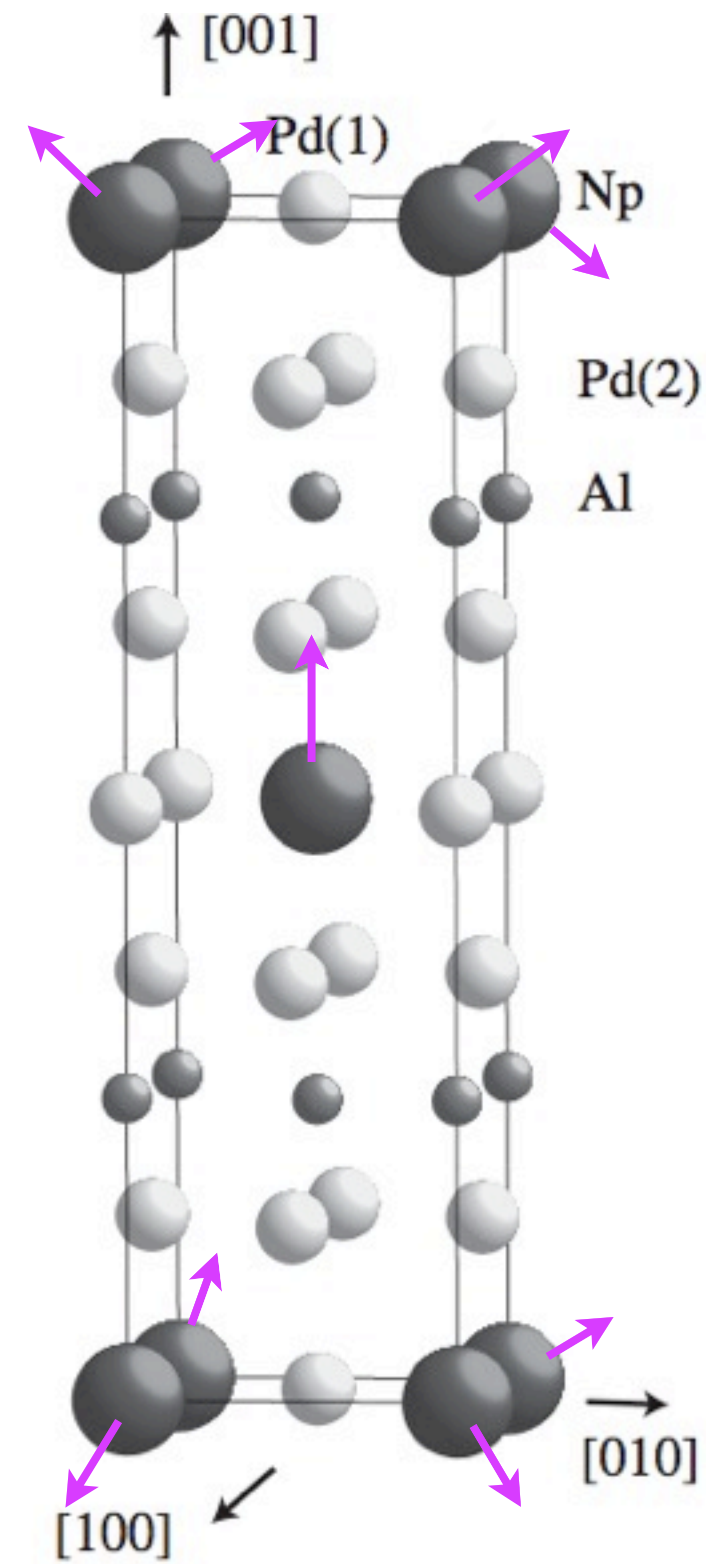

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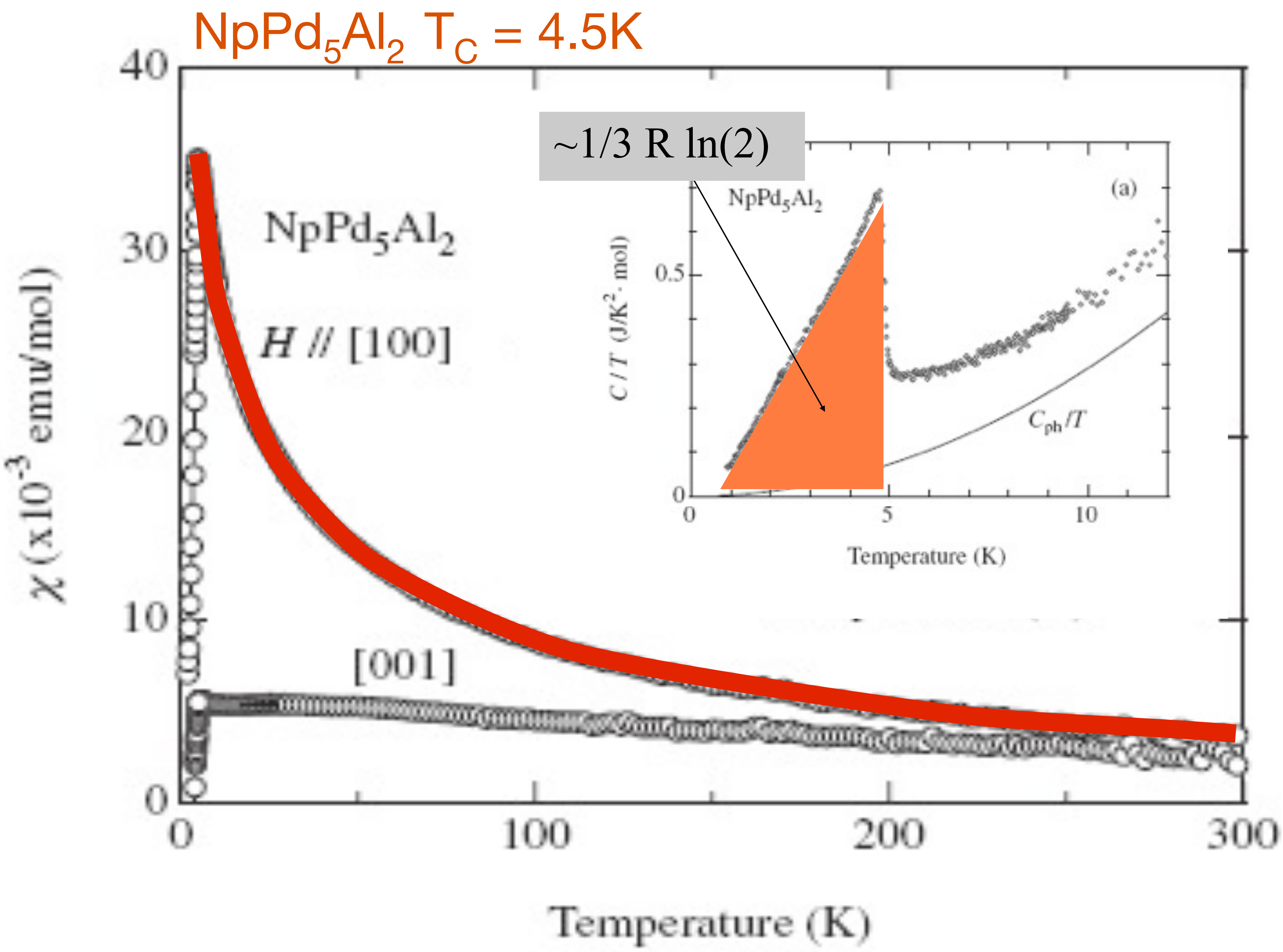

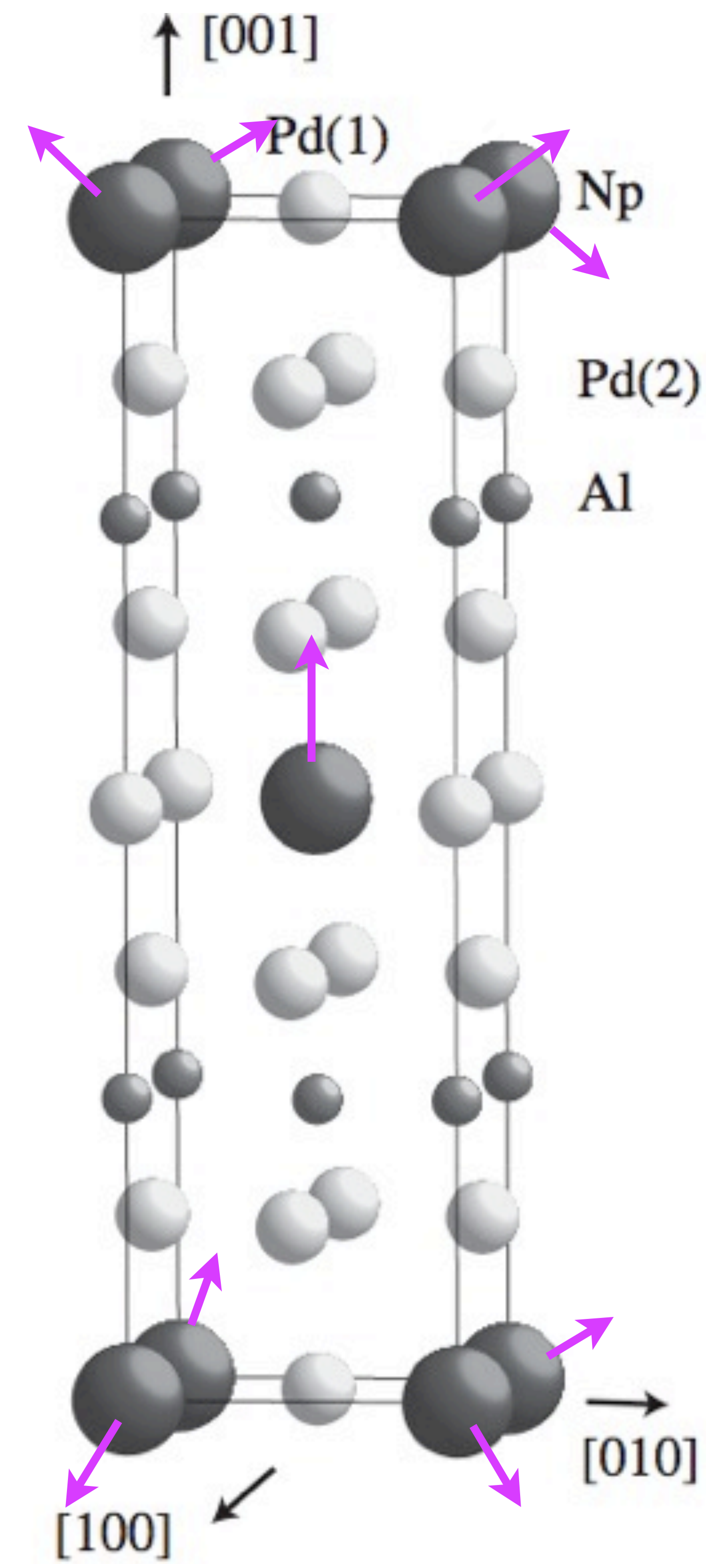

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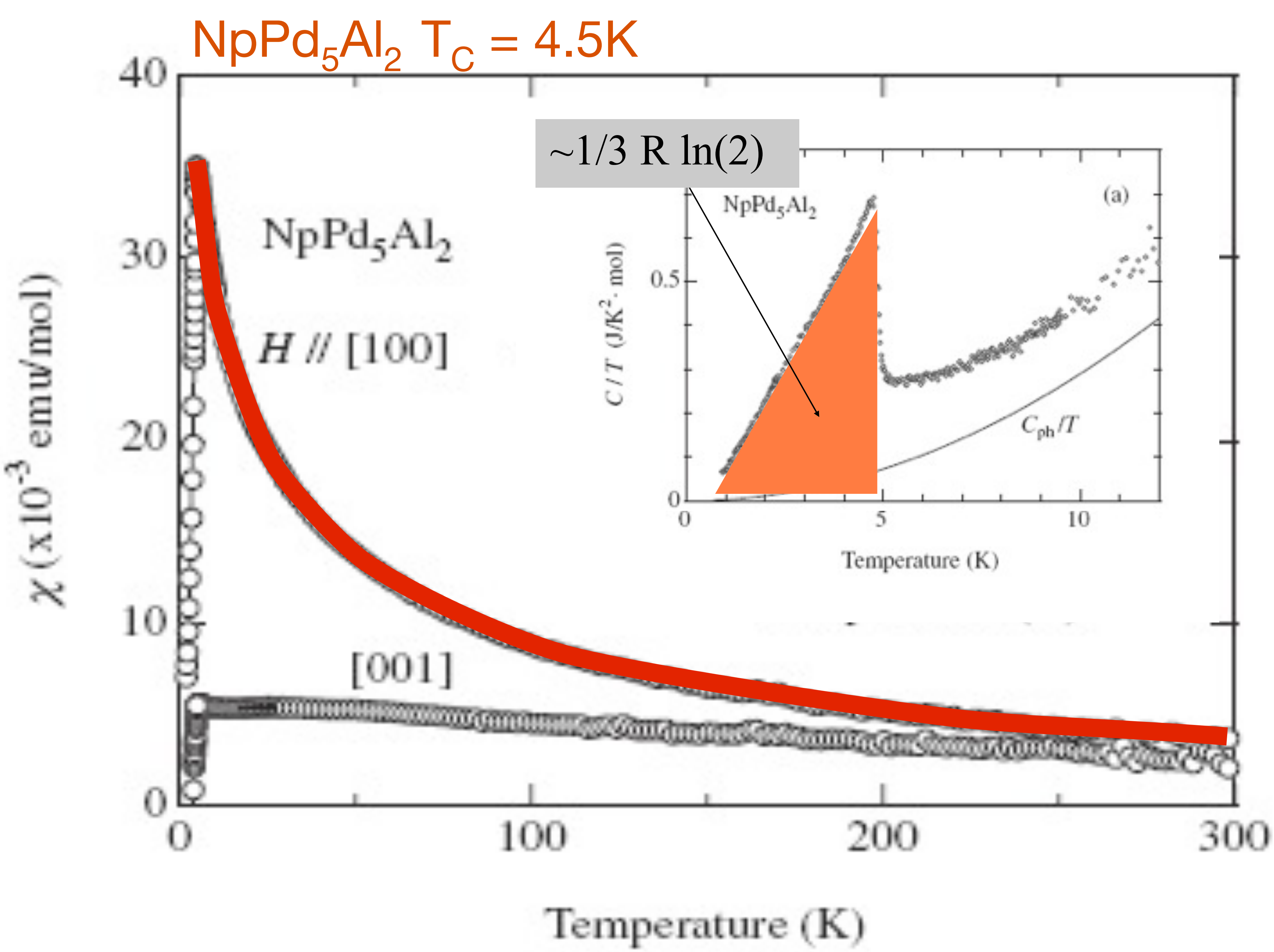
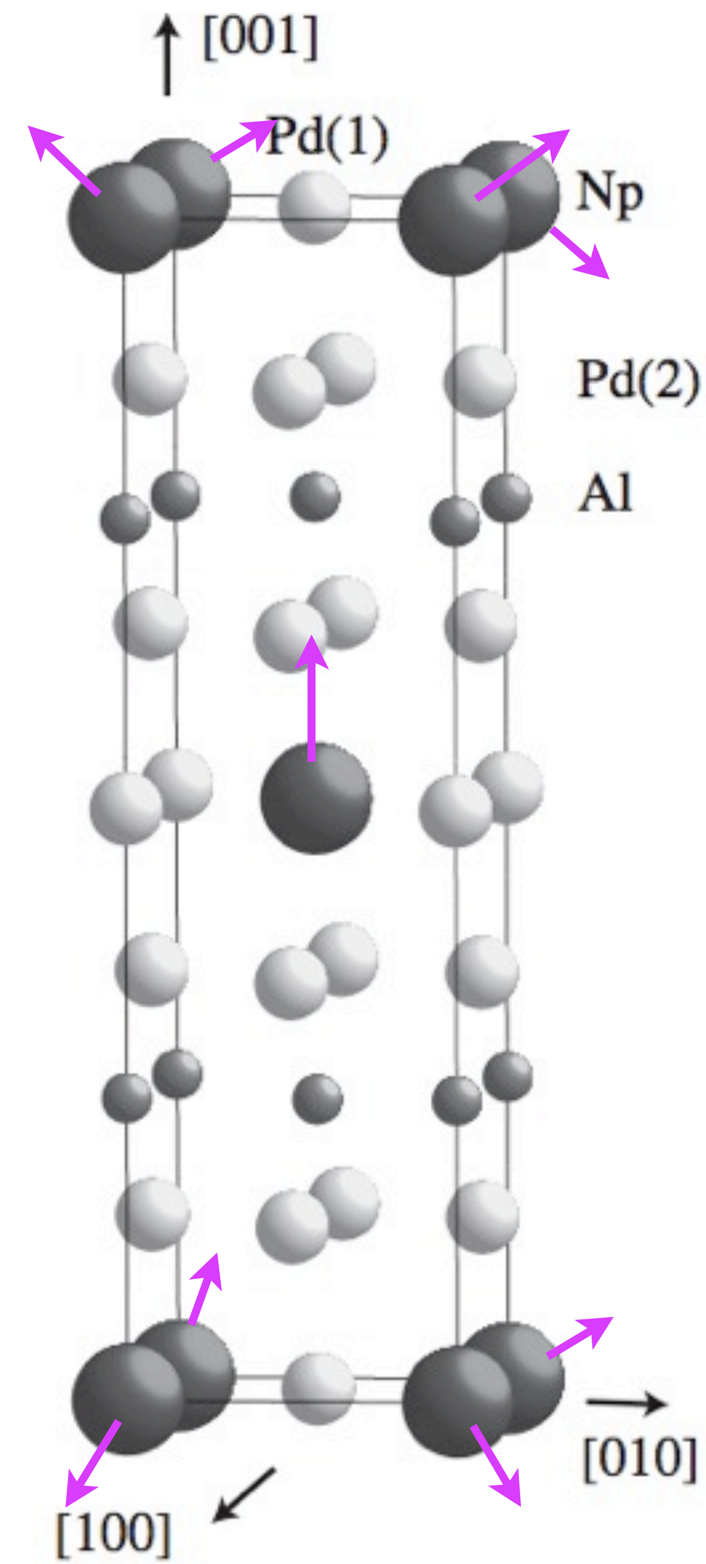
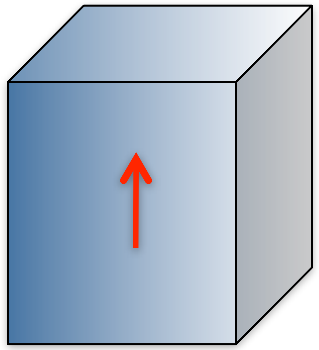




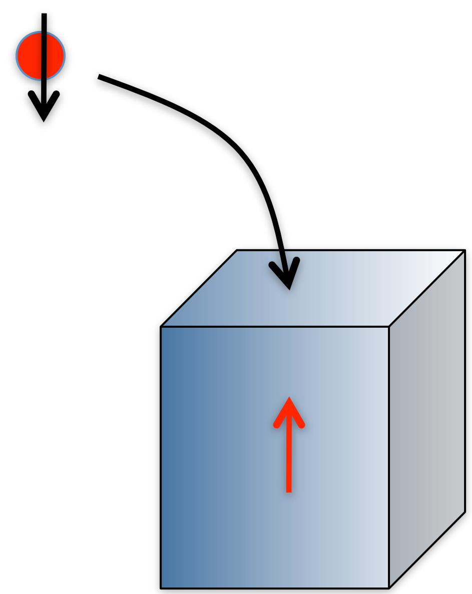
How does the spin form the condensate?

4.5K Heavy Fermion S.C
$NpAl_2Pd_5$
Aoki et al 2007

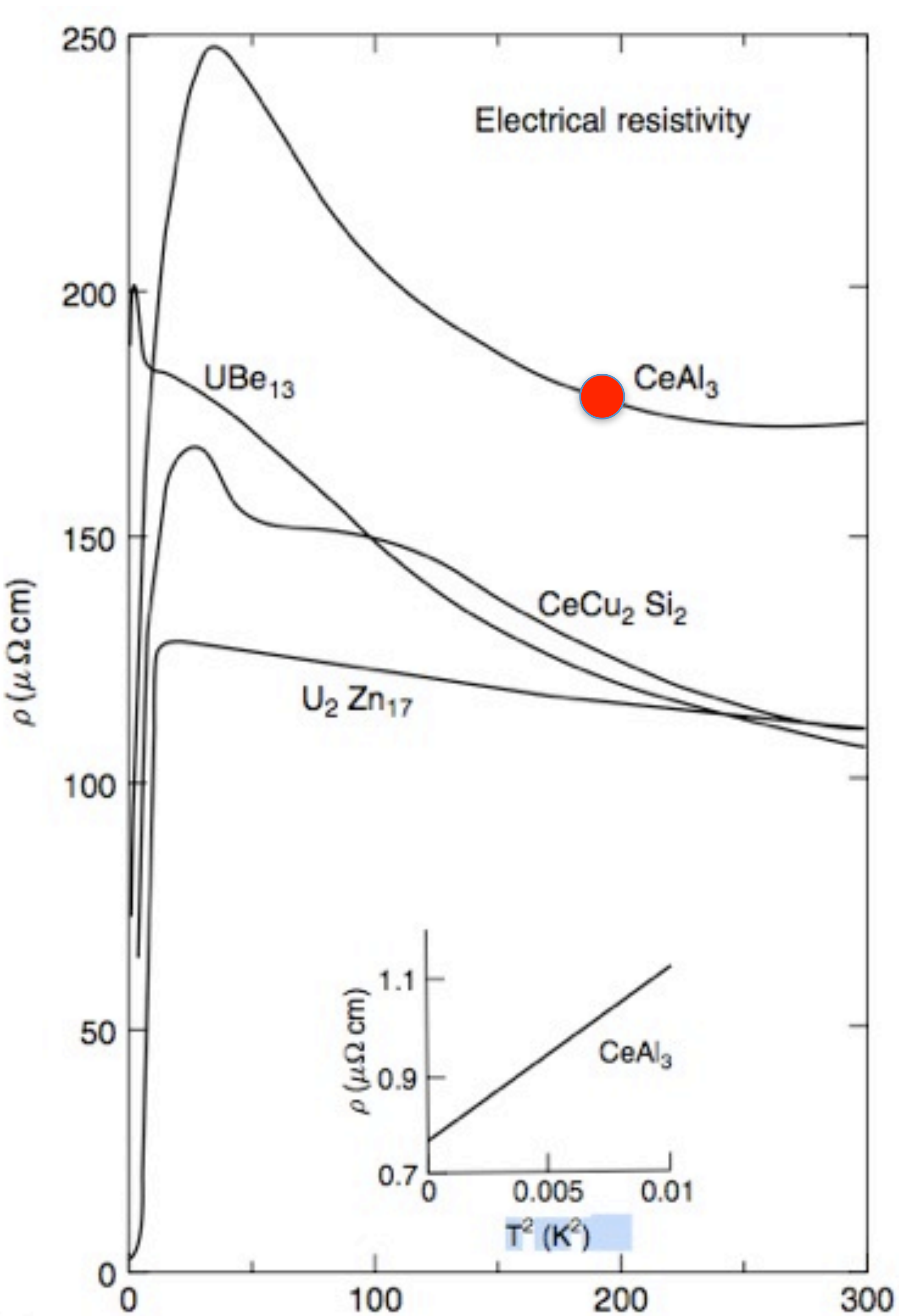
Coherence and composite fermions

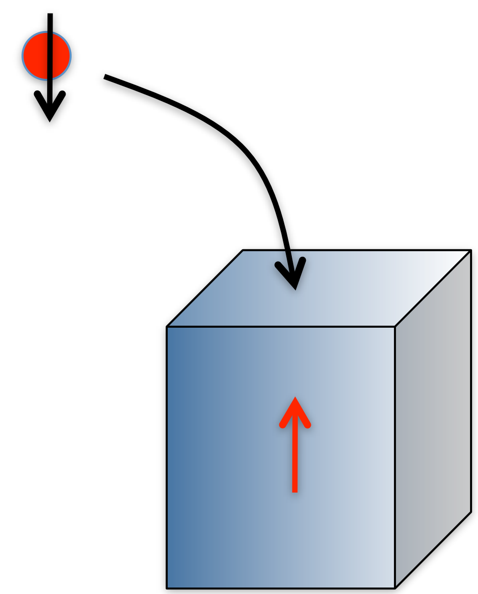


Coherence and composite fermions

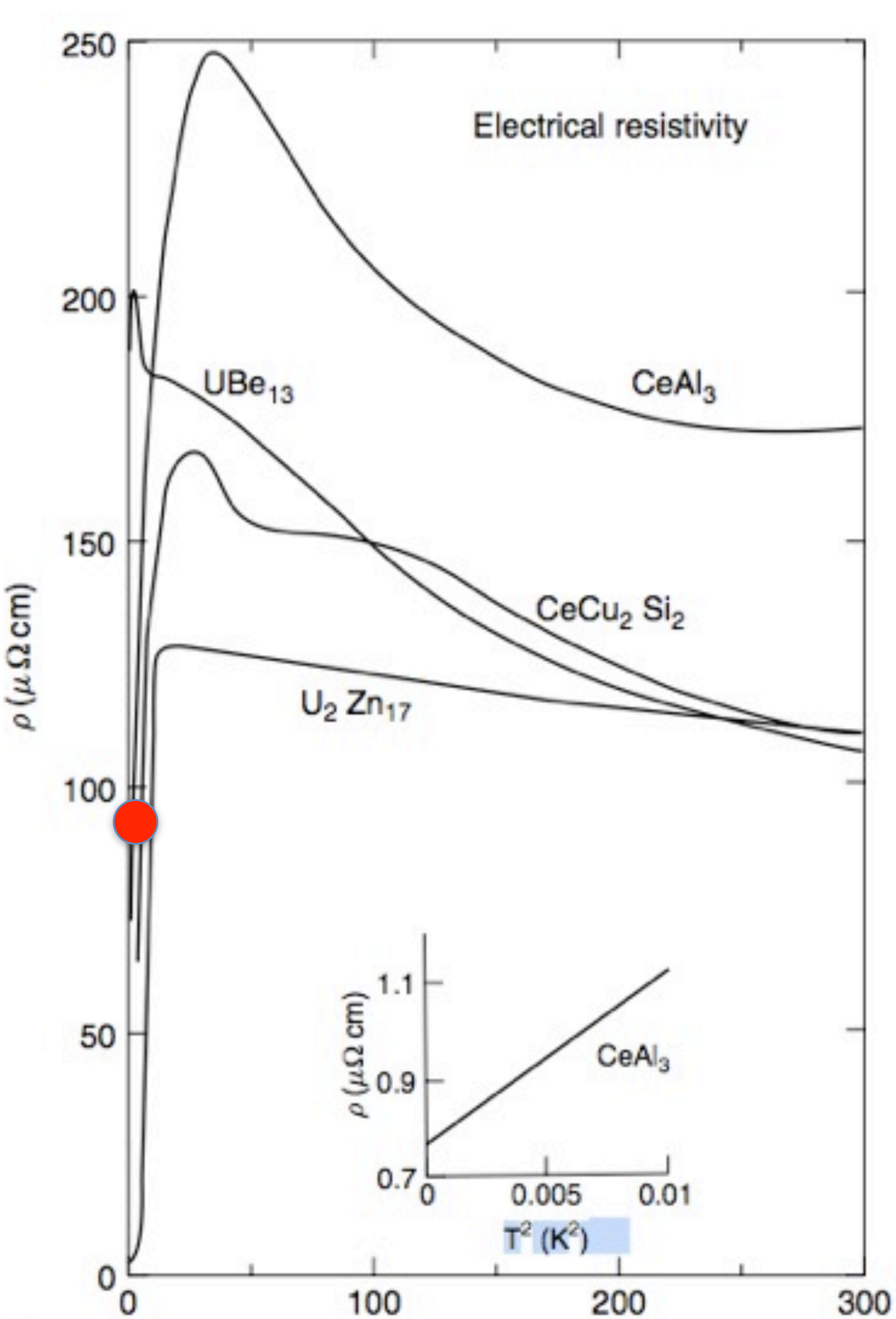


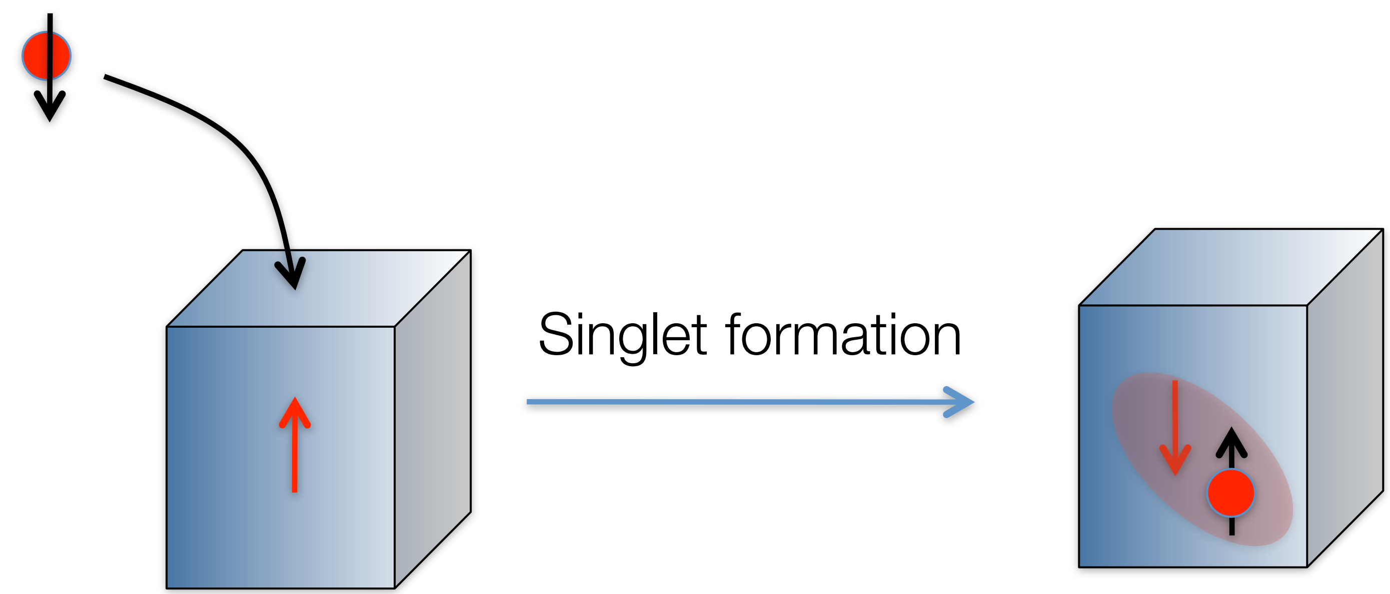
Coherence and composite fermions



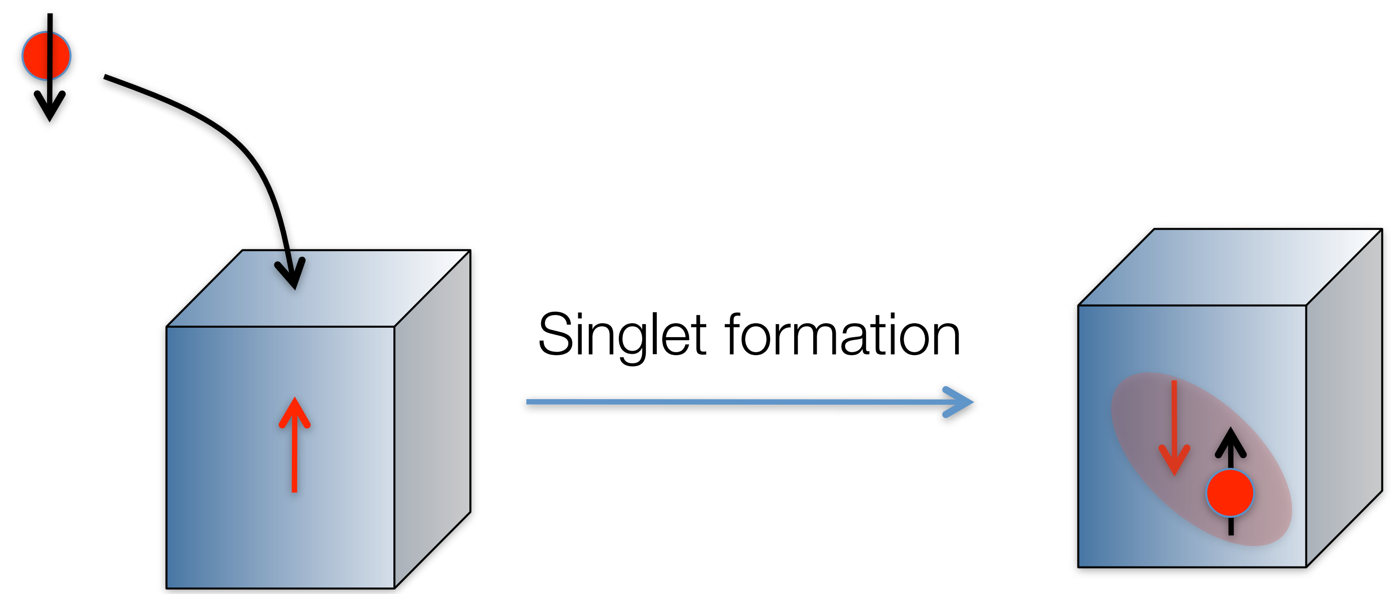


Coherence and composite fermions





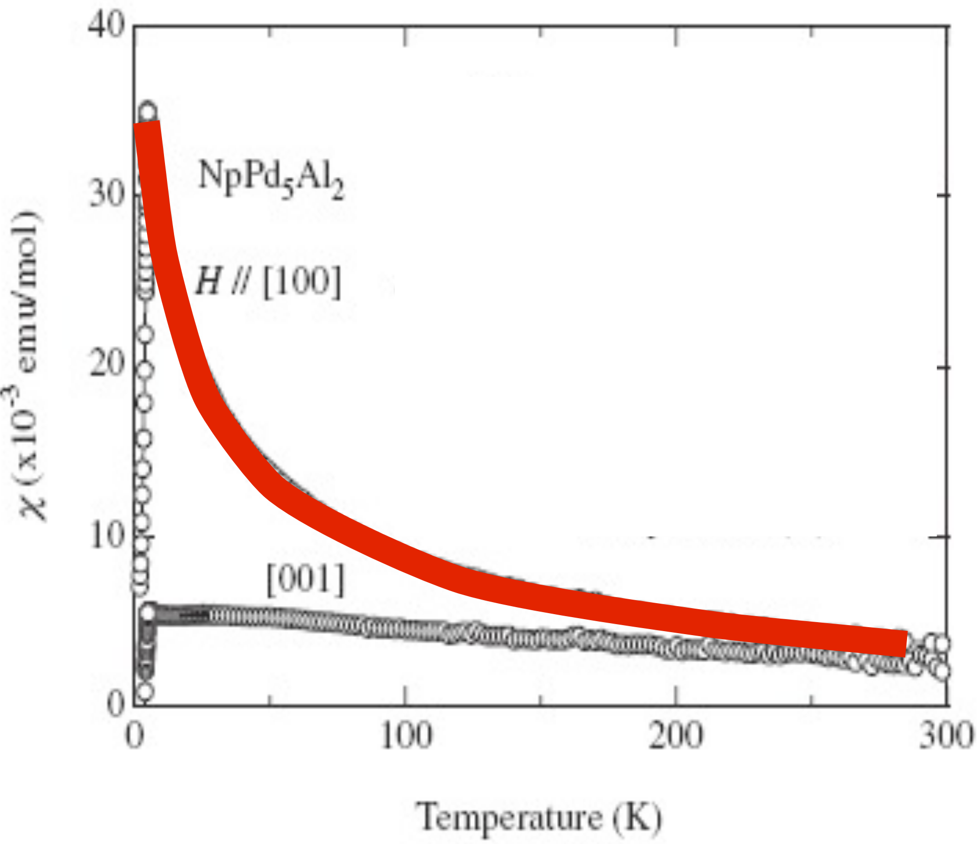
Coherence and composite fermions

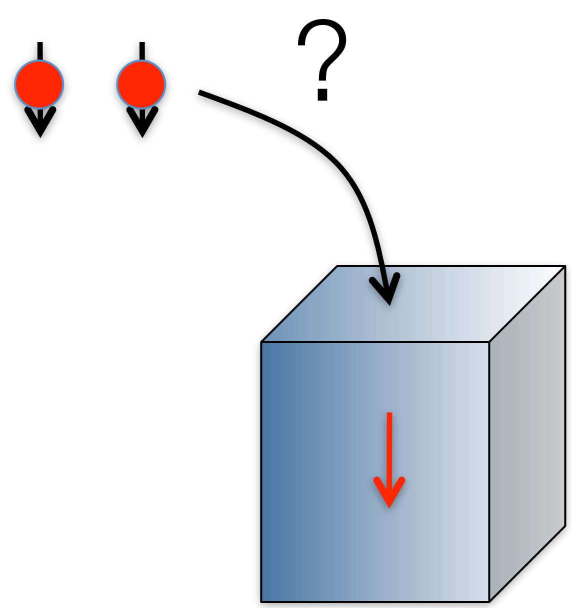


Heavy electron = (electron x spinflip)

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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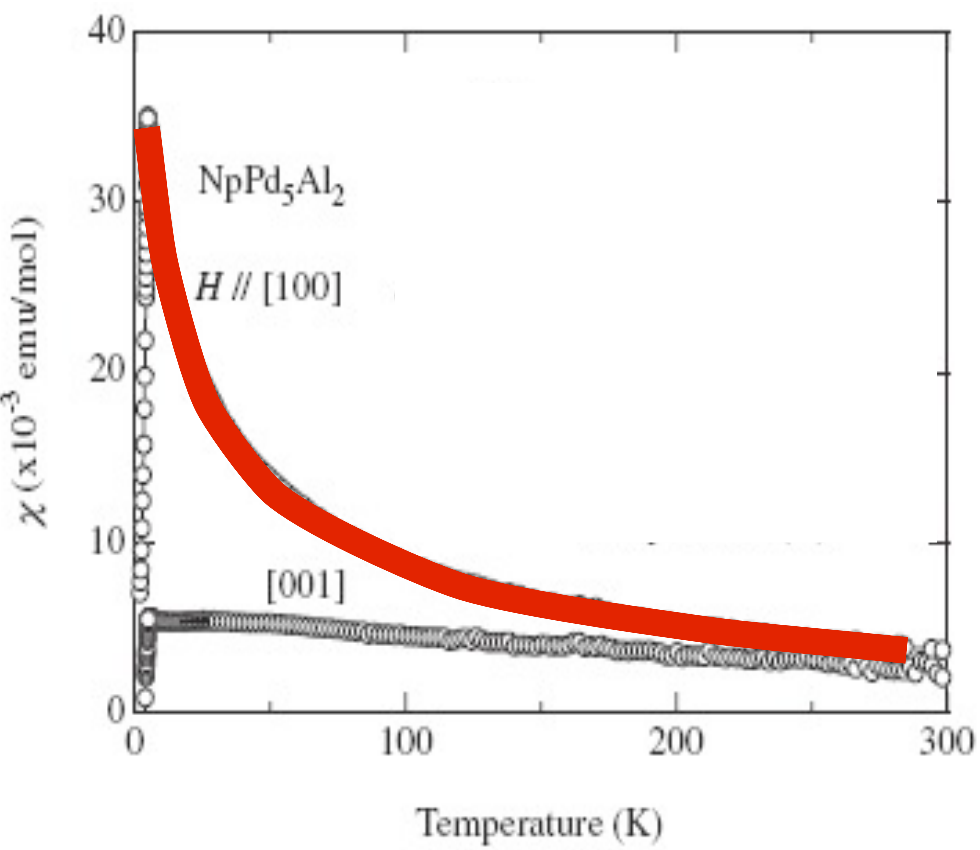

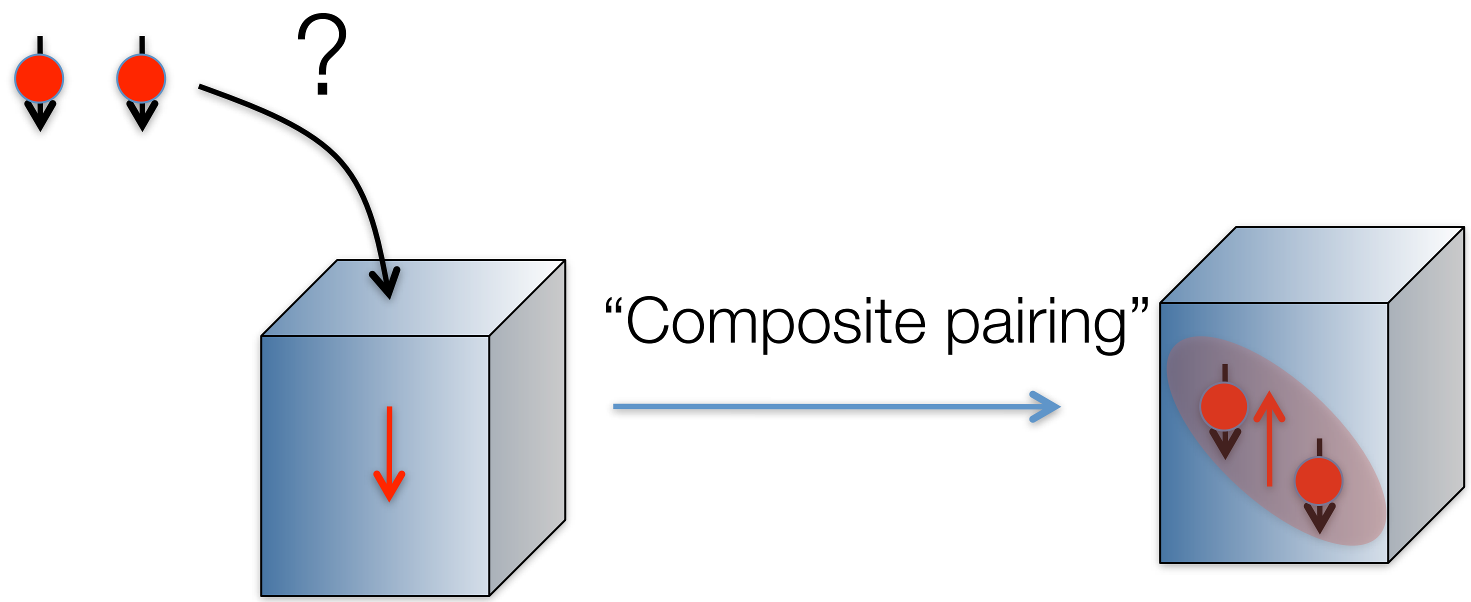

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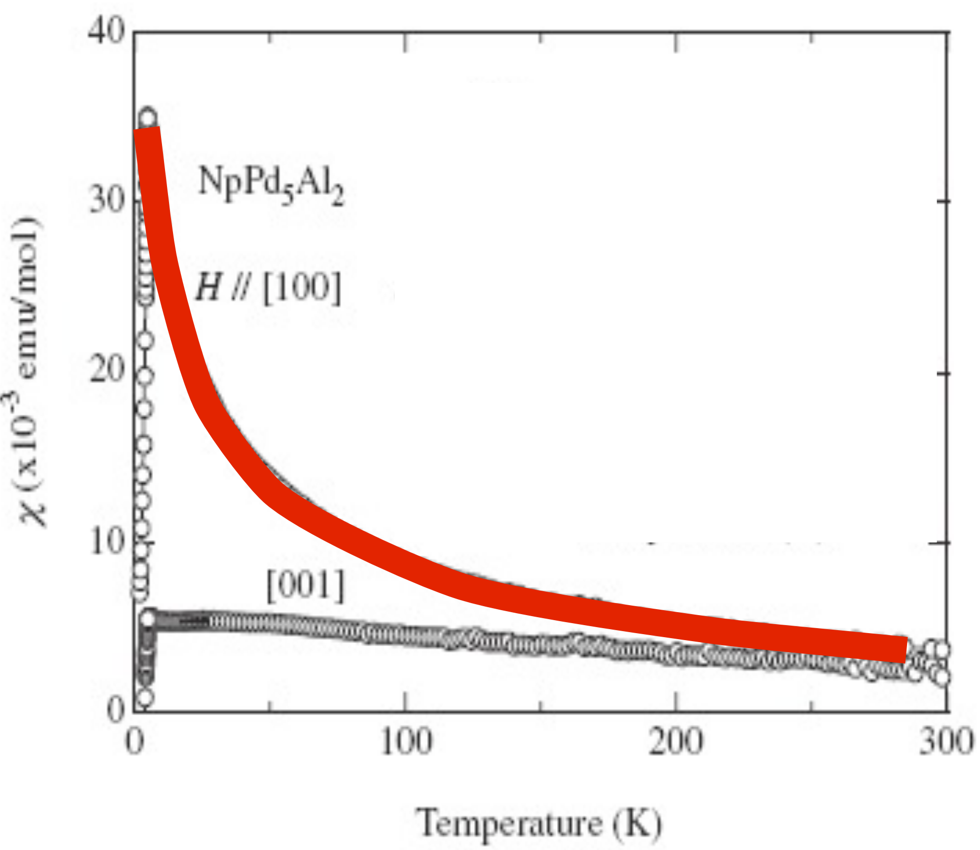

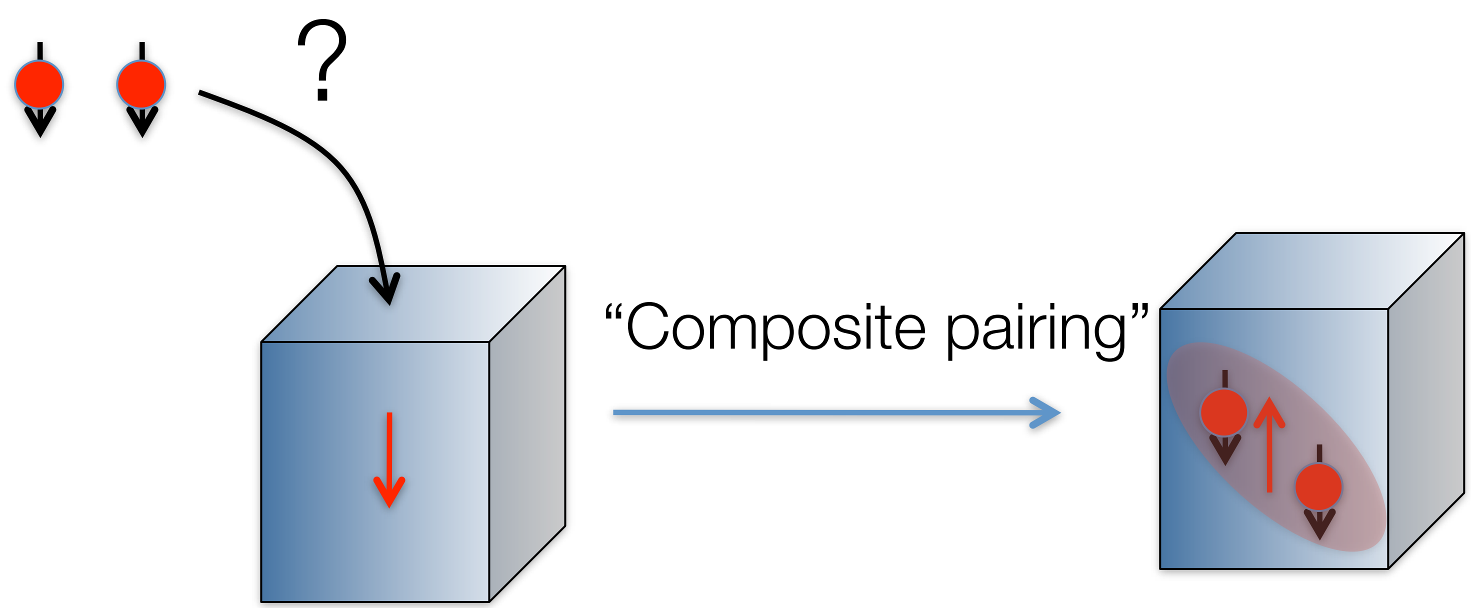

Heavy Cooper pair = (pair x spinflip)

Composite pairing

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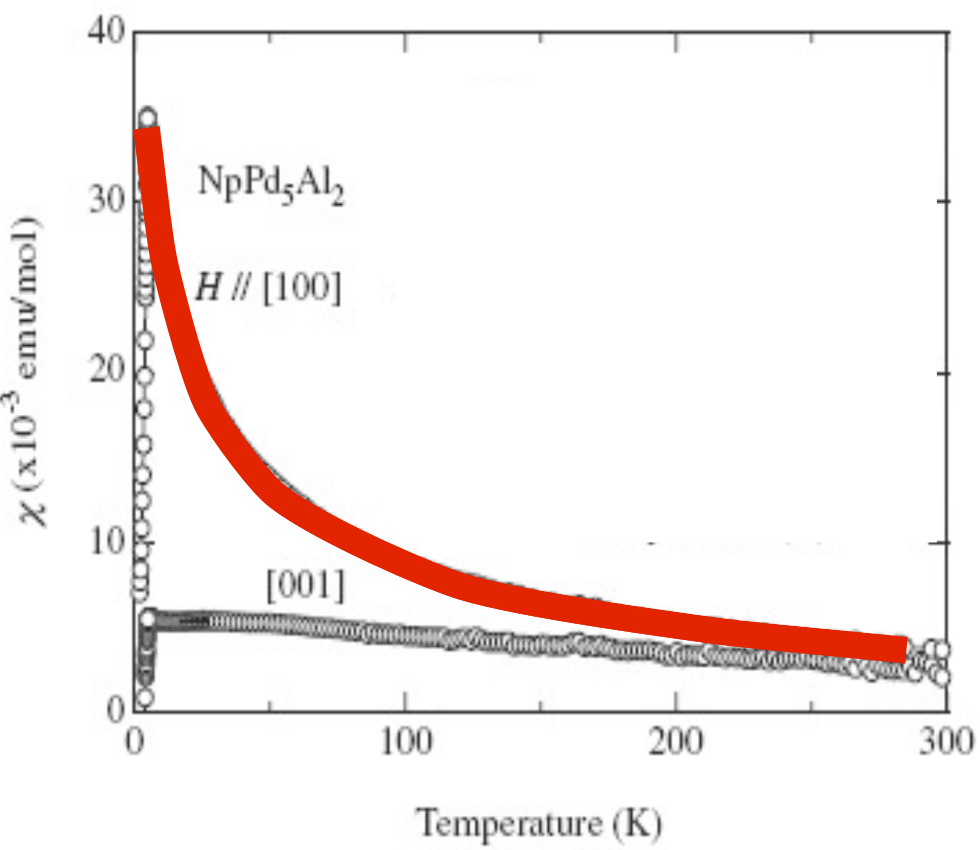
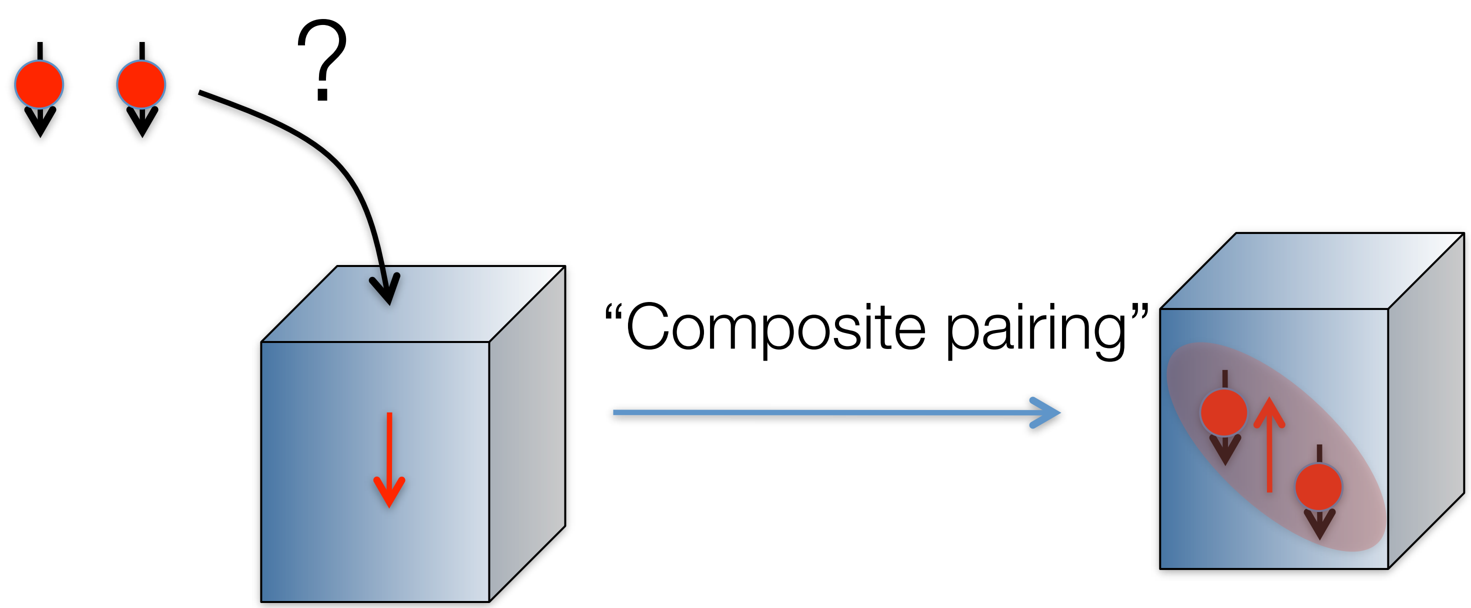


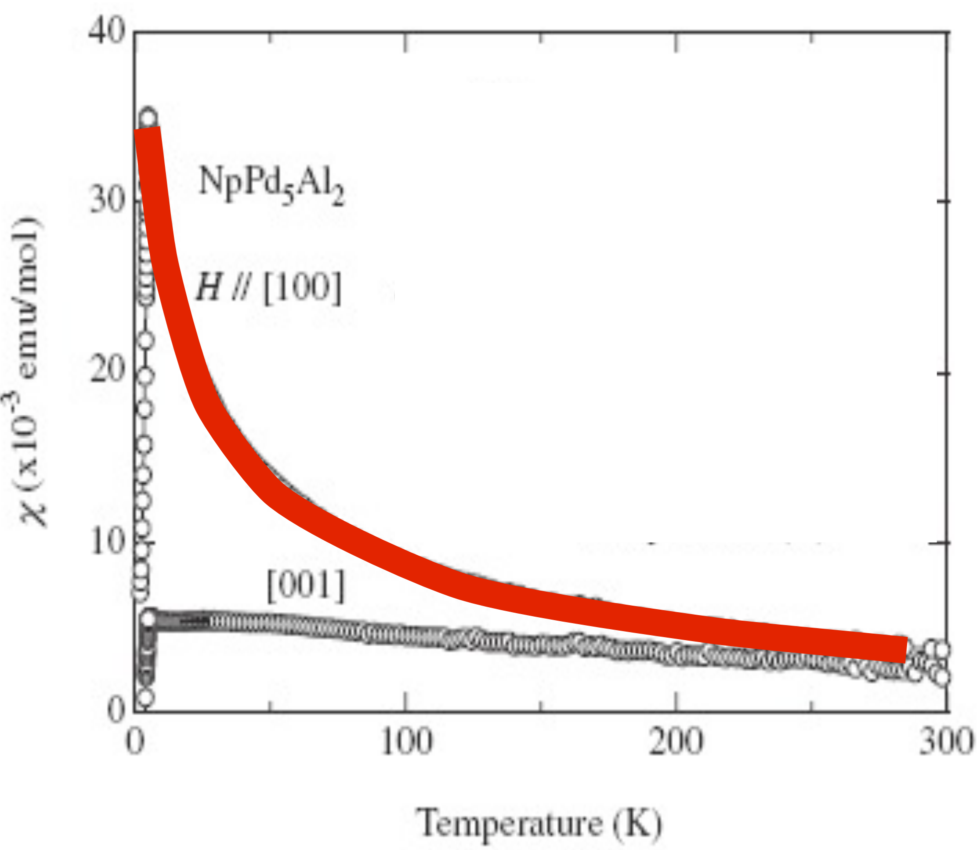


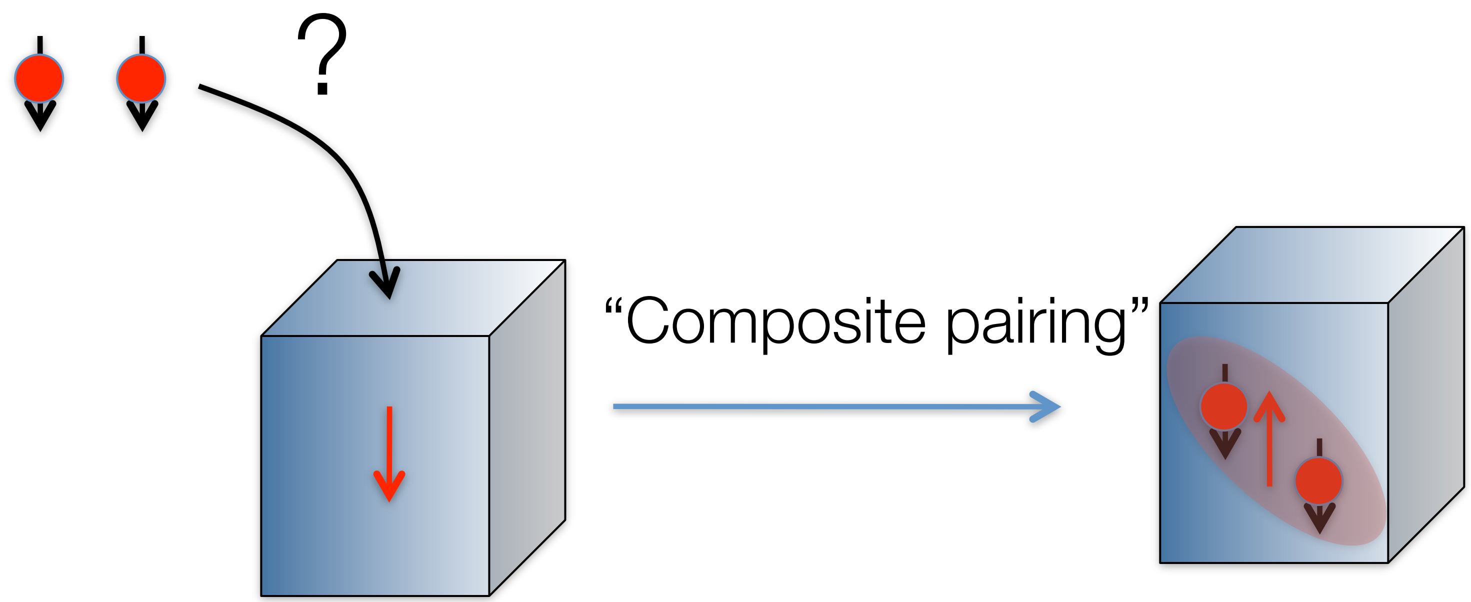
Heavy Cooper pair = (pair x spinflip)

$$\Psi^\dagger = c^\dagger_{1\downarrow} c^\dagger_{2\downarrow} S_+$$

Composite pairing

$NpPd_5Al_2$ $T_C = 4.5K$





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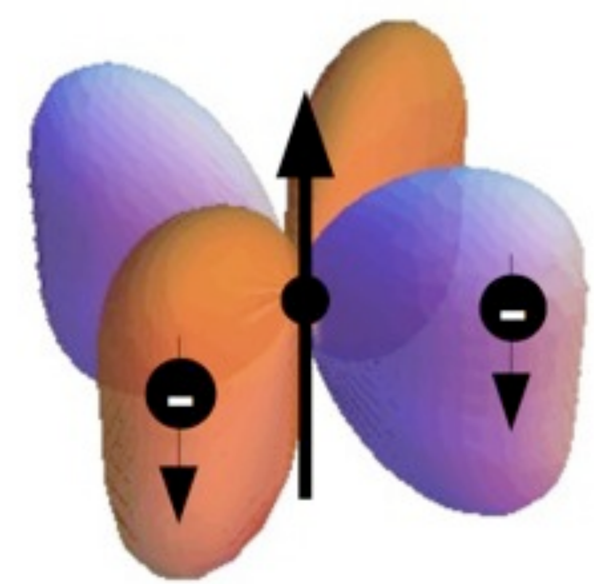
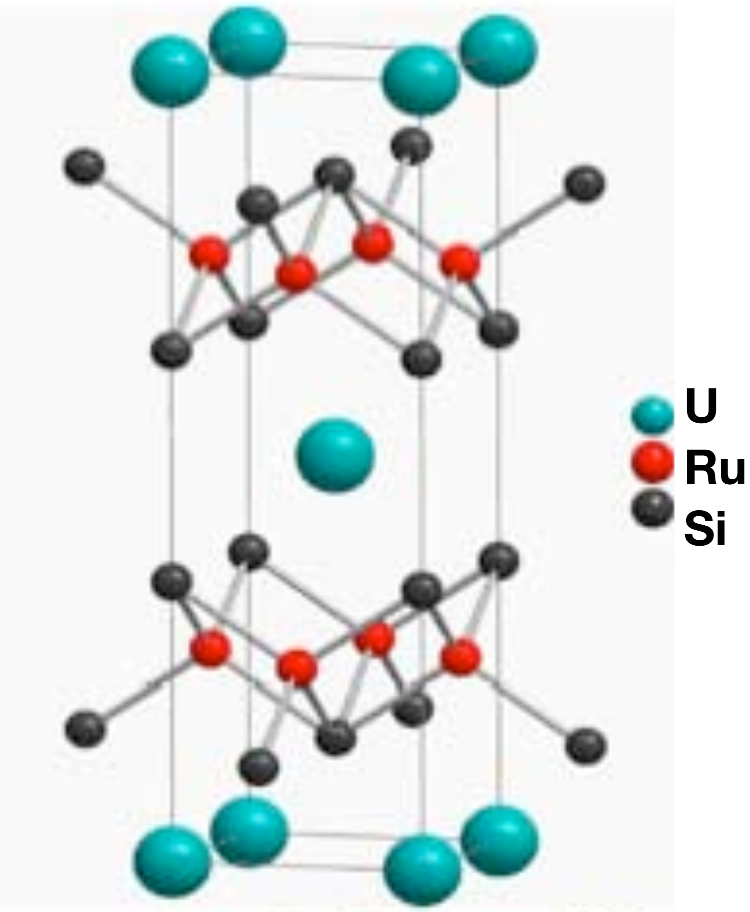
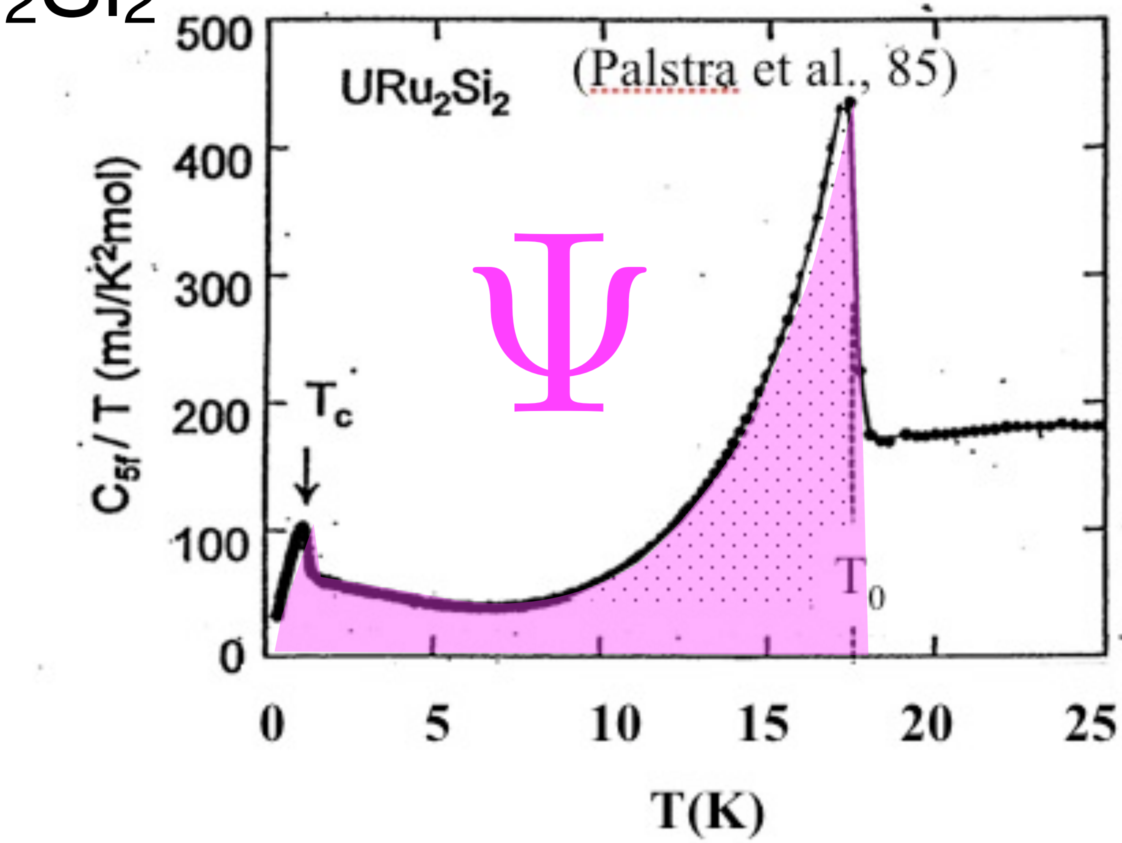
Abrahams, Balatsky, Scalapino, Schrieffer 1995
Flint, Dzero and Coleman, 2009.



Mystery III : Hidden Order URu_2Si_2





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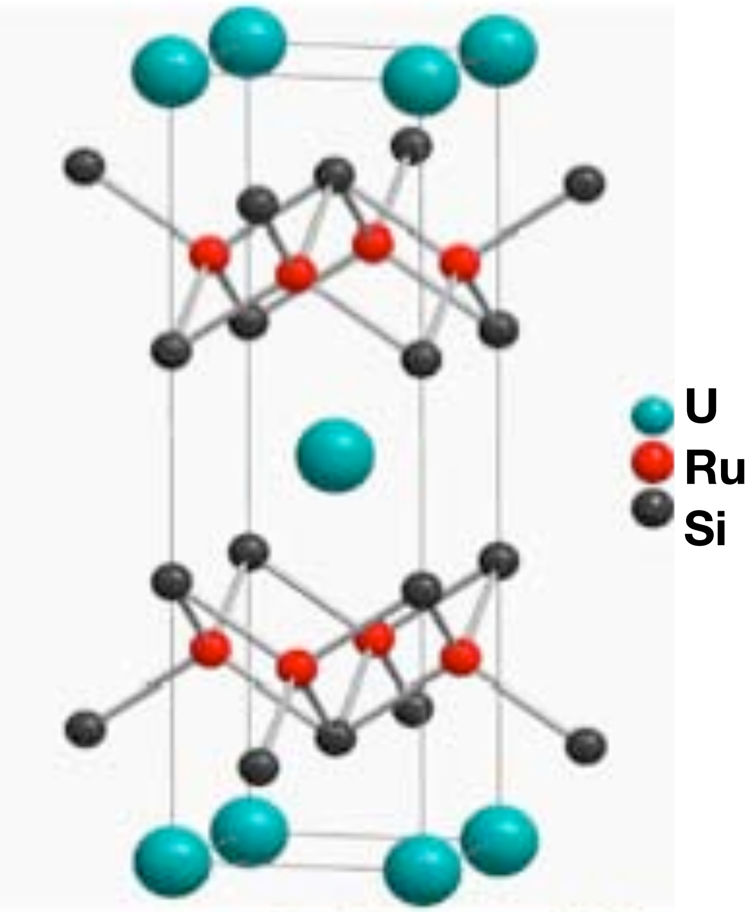
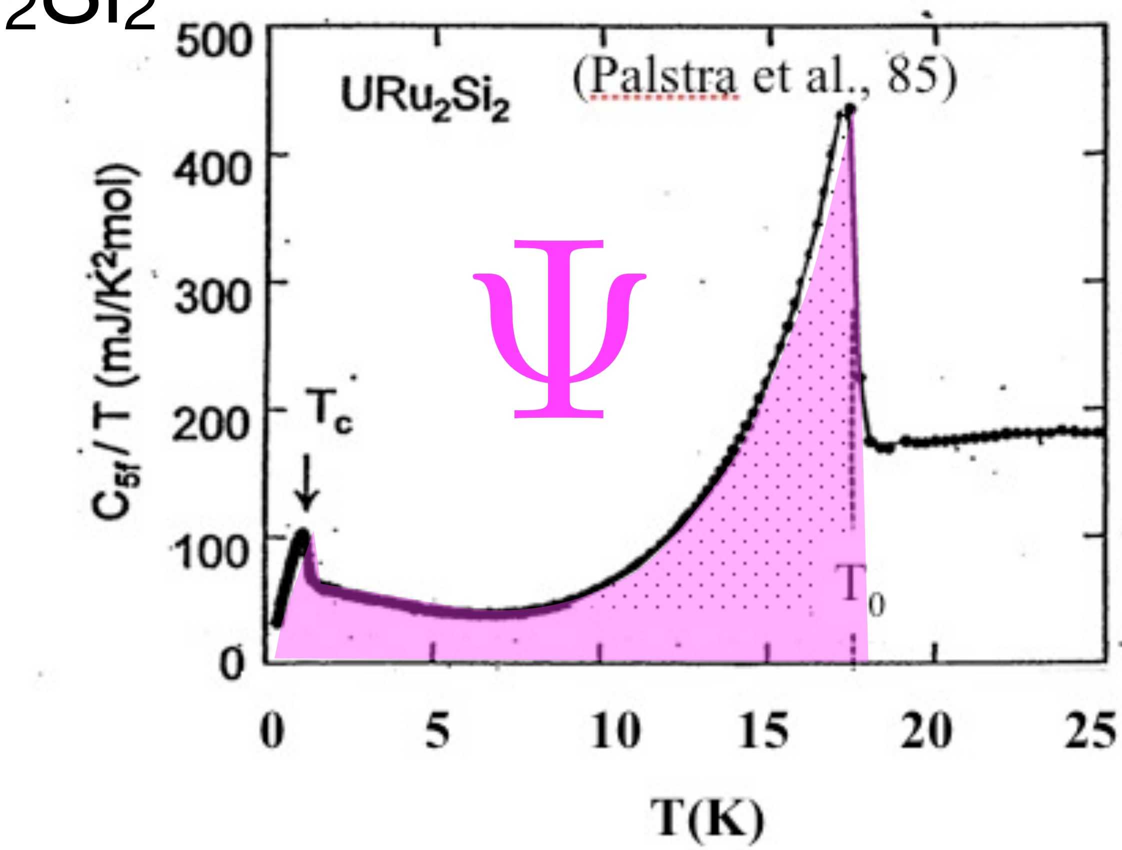
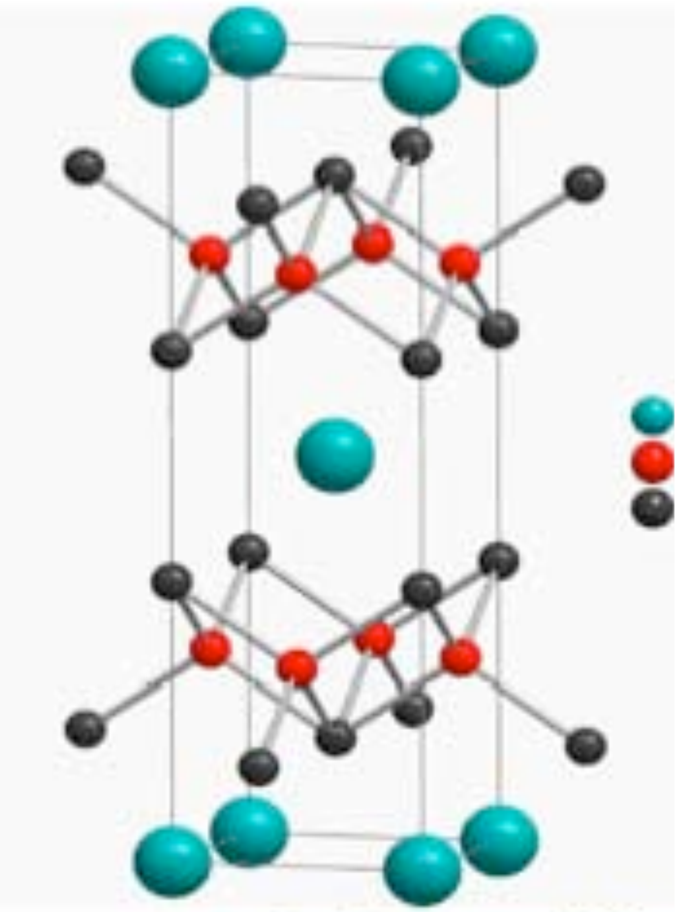
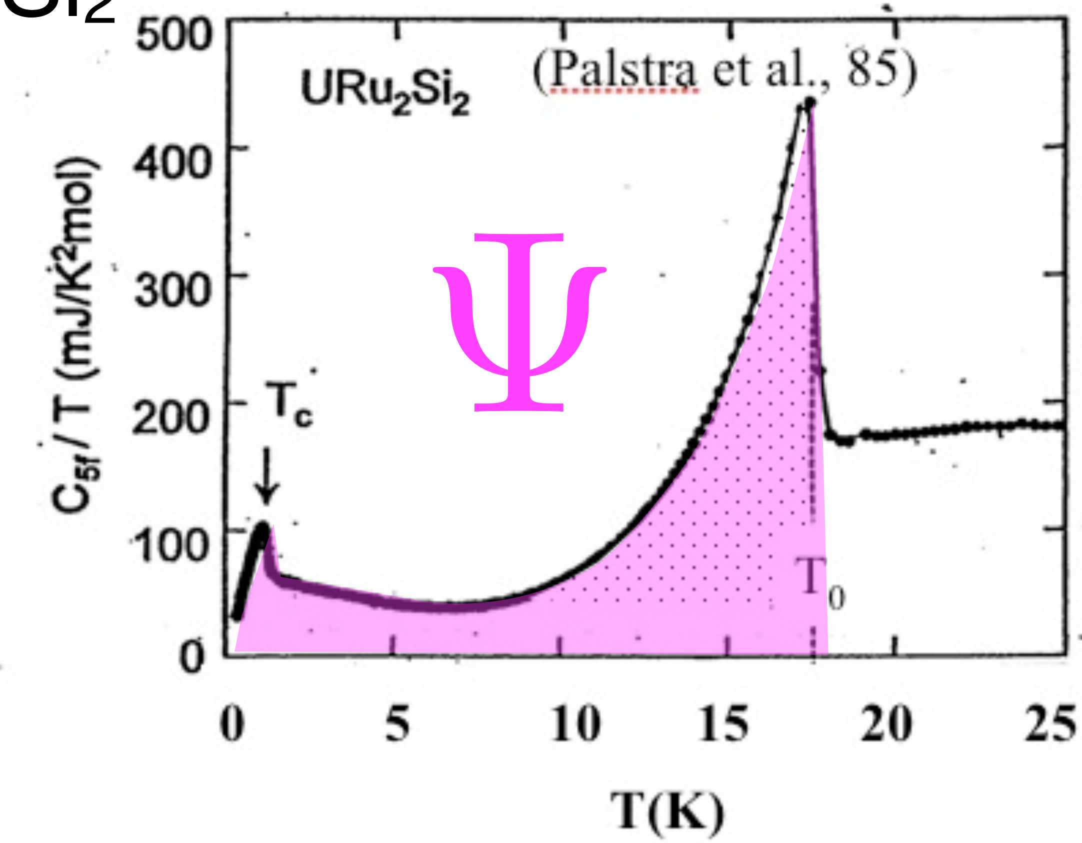




$$\Delta S = \int_0^{T_0} \frac{C_V}{T} dT \sim 0.36 R \ln 2$$

Mystery III : Hidden Order URu_2Si_2





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Large entropy of condensation.

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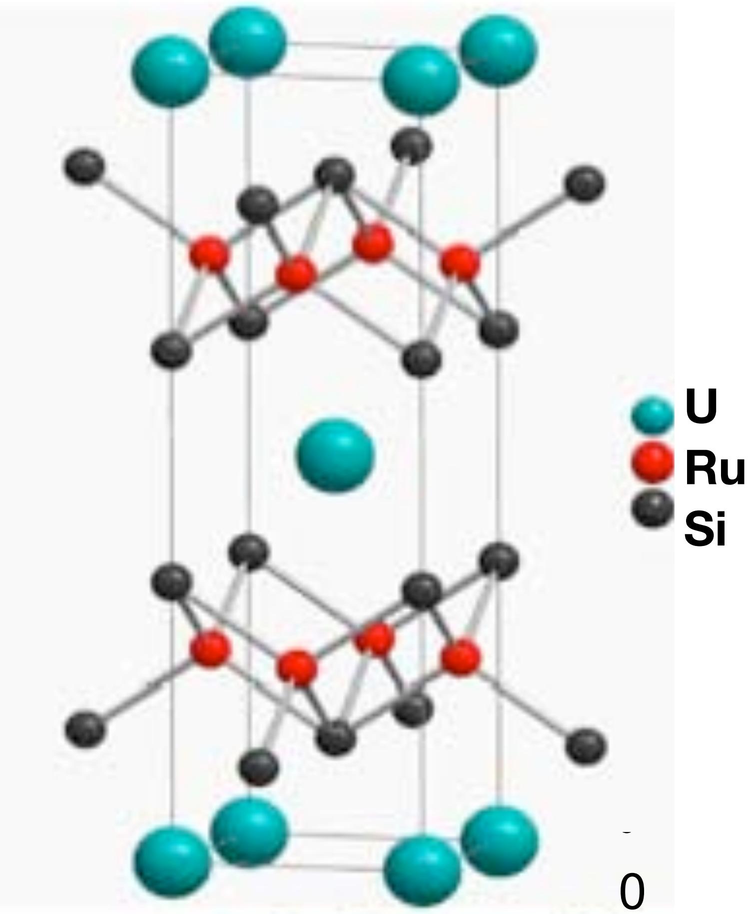

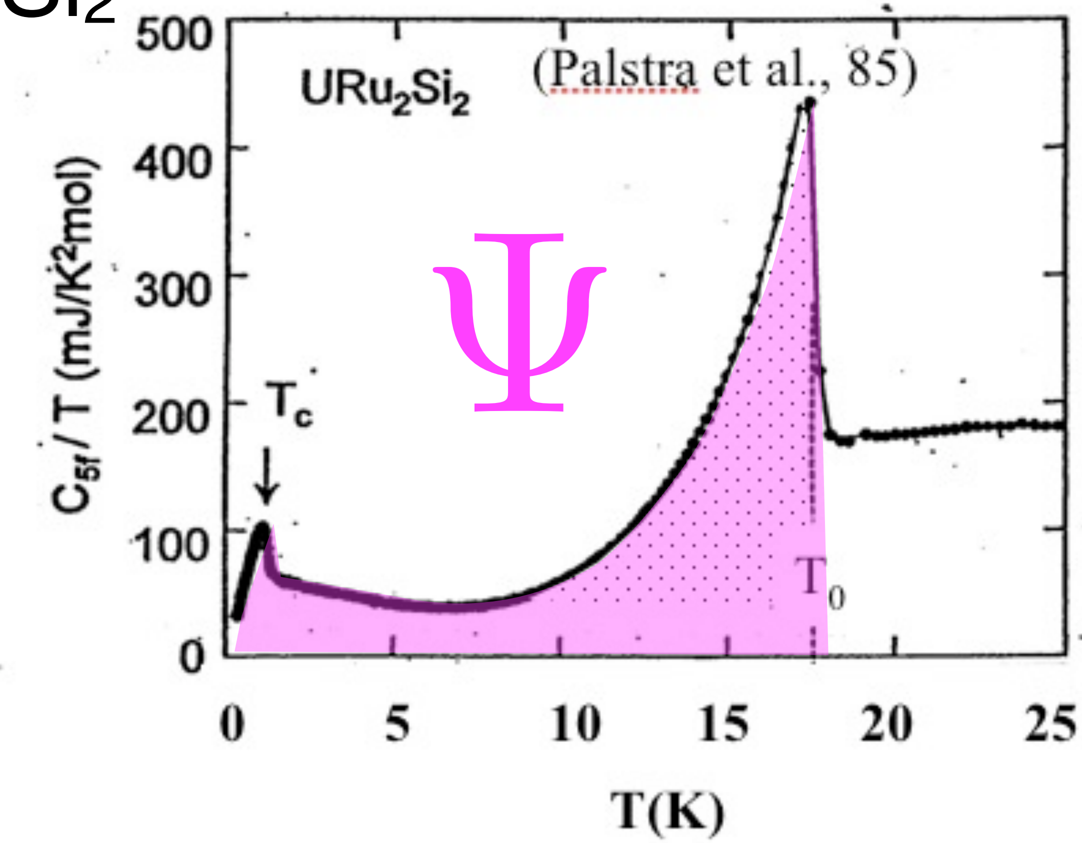

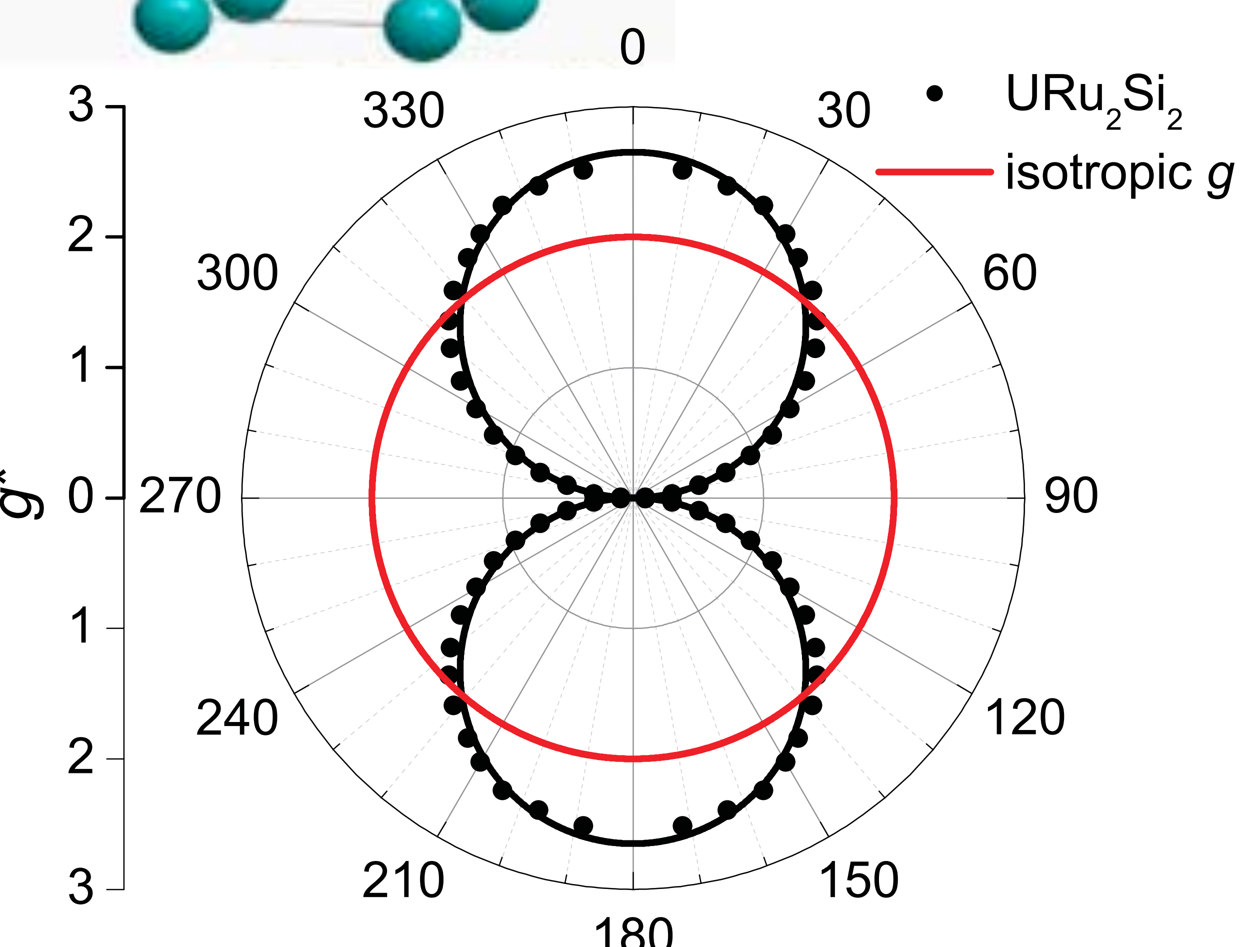

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Large entropy of condensation.
Quasiparticles with Giant Ising Anisotropy. (Harrison et al.)

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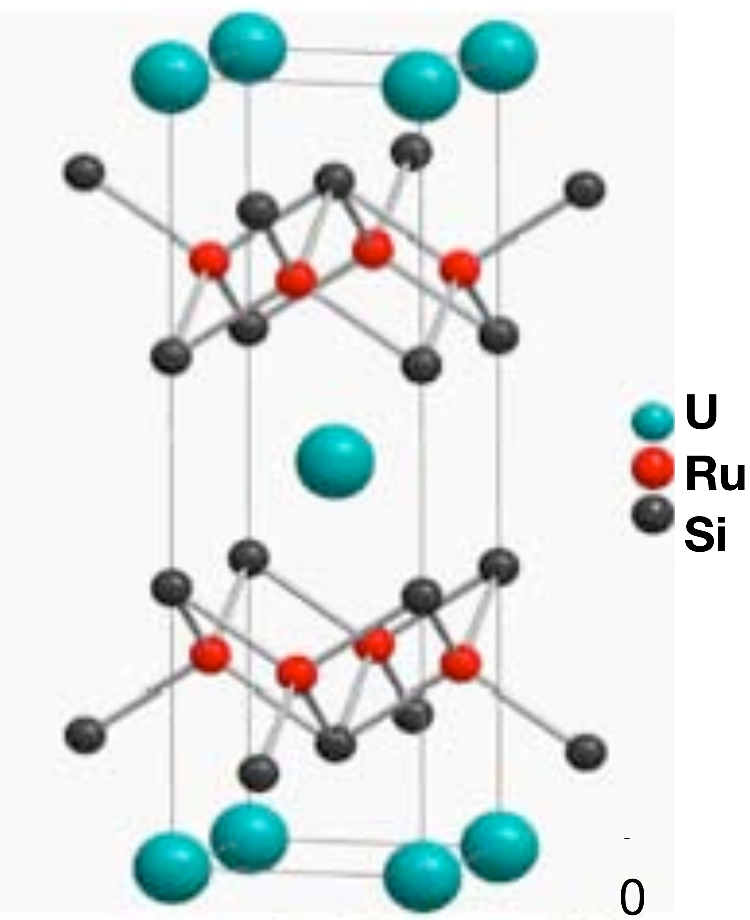

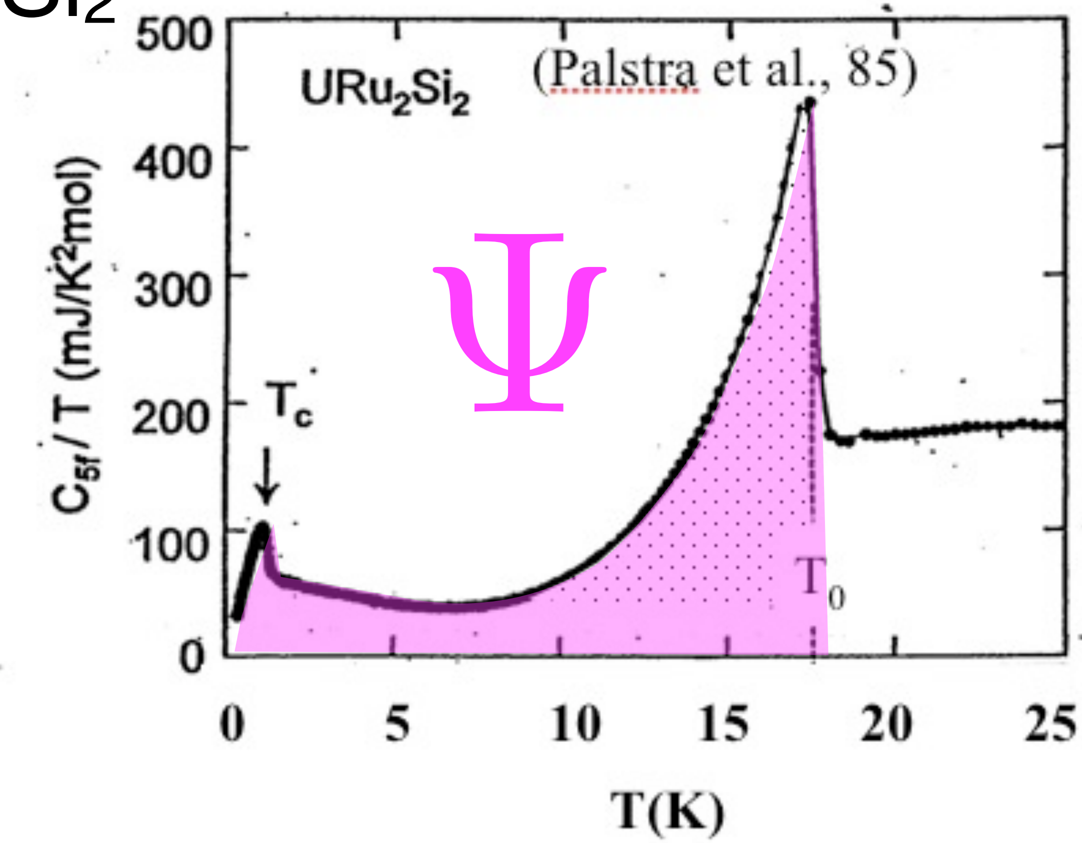

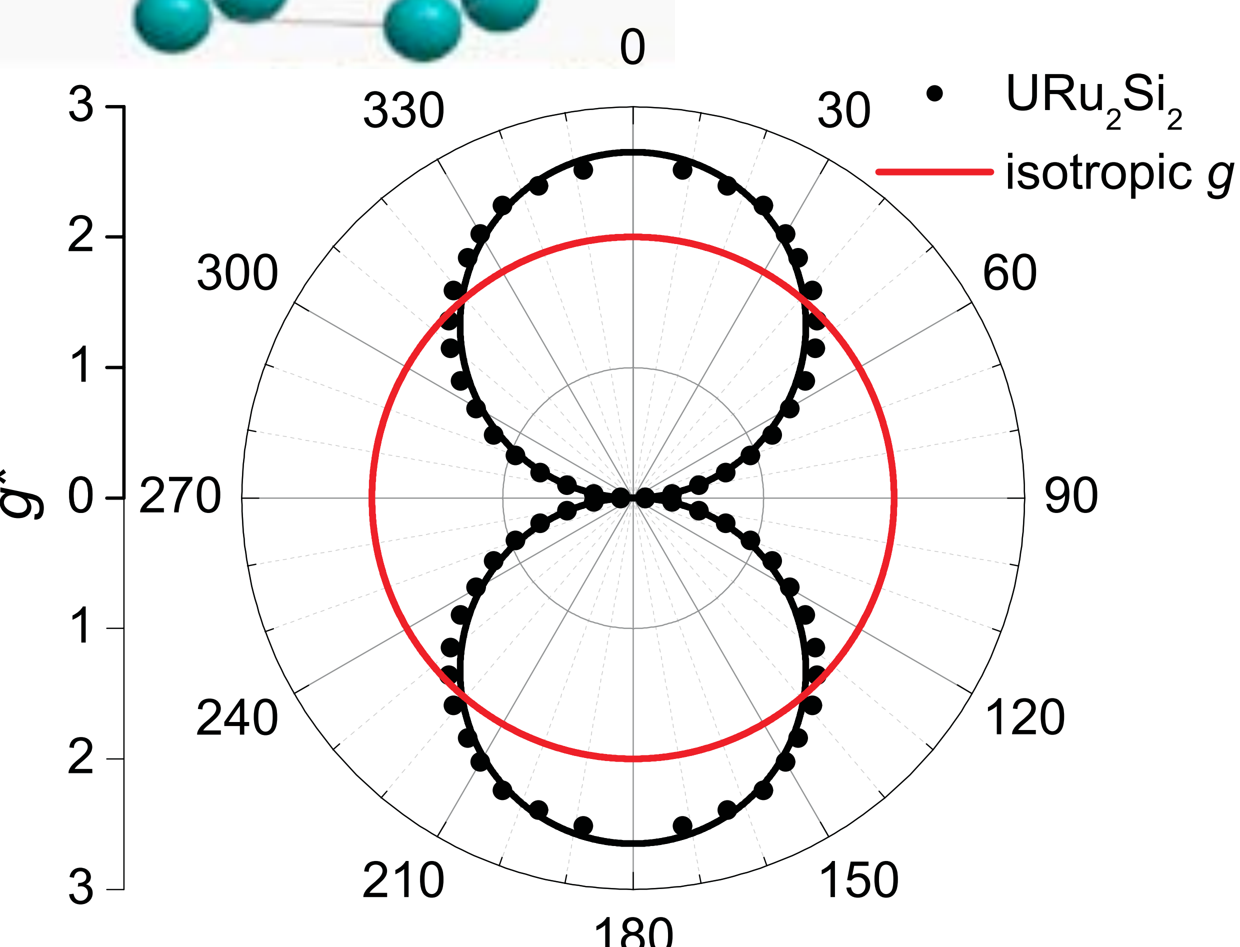

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Large entropy of condensation. Quasiparticles with Giant Ising Anisotropy. (Harrison et al.)

What is the nature of the hidden order?

Mystery IV :
Topology and Heavy Fermions?

Collaborators:

Maxim Dzero, Kent State University.
Kai Sun, University of Maryland
Victor Galitski, University of Maryland

Phys. Rev. Lett. 104, 106408 (2010).
arXiv:1108.3371

Kai Maxim Victor

Rutgers Center for Materials Theory

Kondo Insulators: SmB_6

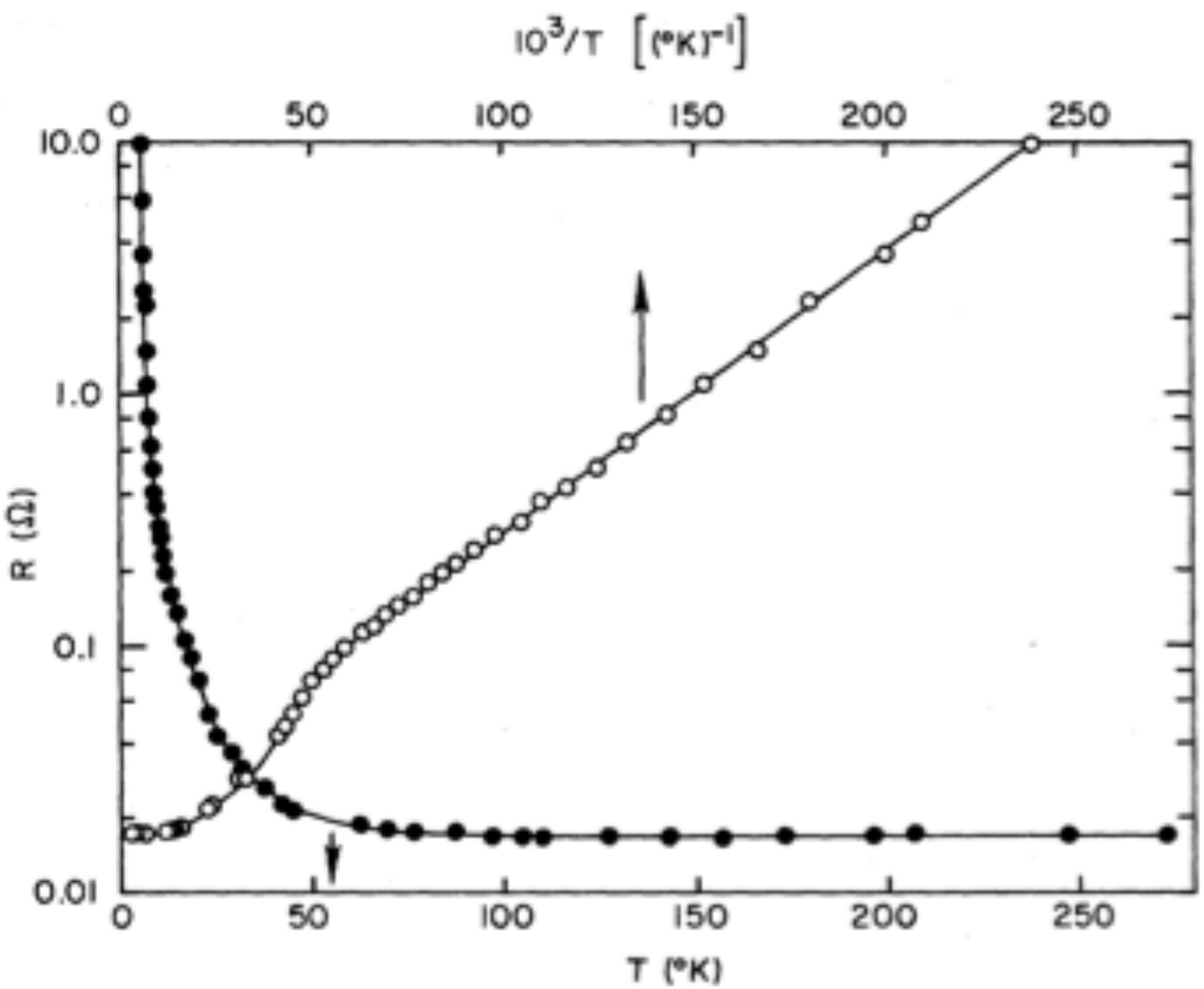
MAGNETIC AND SEMICONDUCTING PROPERTIES OF SmB_6†

A. Menth and E. Buehler
Bell Telephone Laboratories, Murray Hill, New Jersey

and

T. H. Geballe
Department of Applied Physics, Stanford University, Stanford, California,
and Bell Telephone Laboratories, Murray Hill, New Jersey

(Received 21 November 1968)



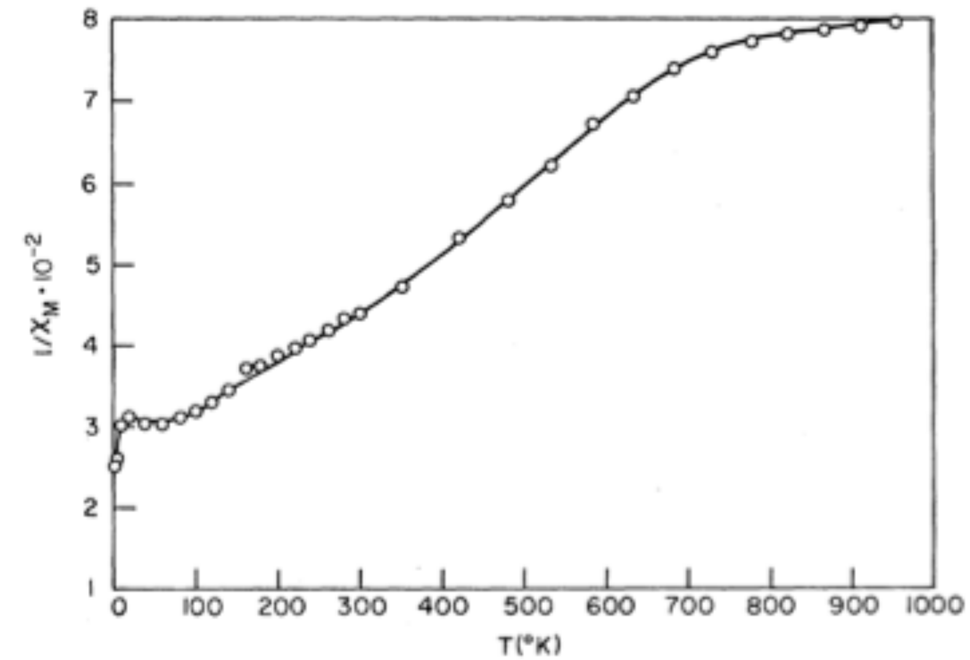
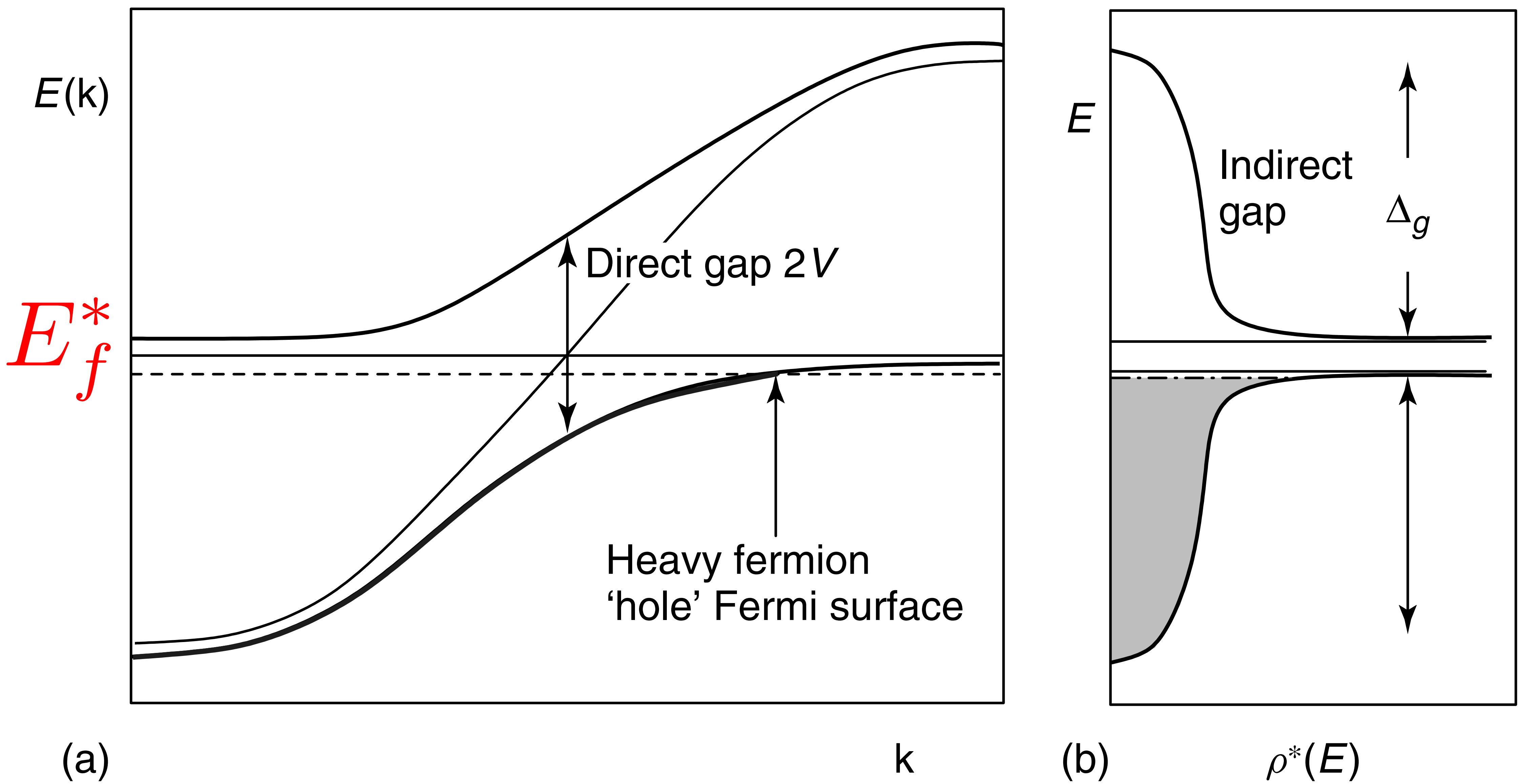


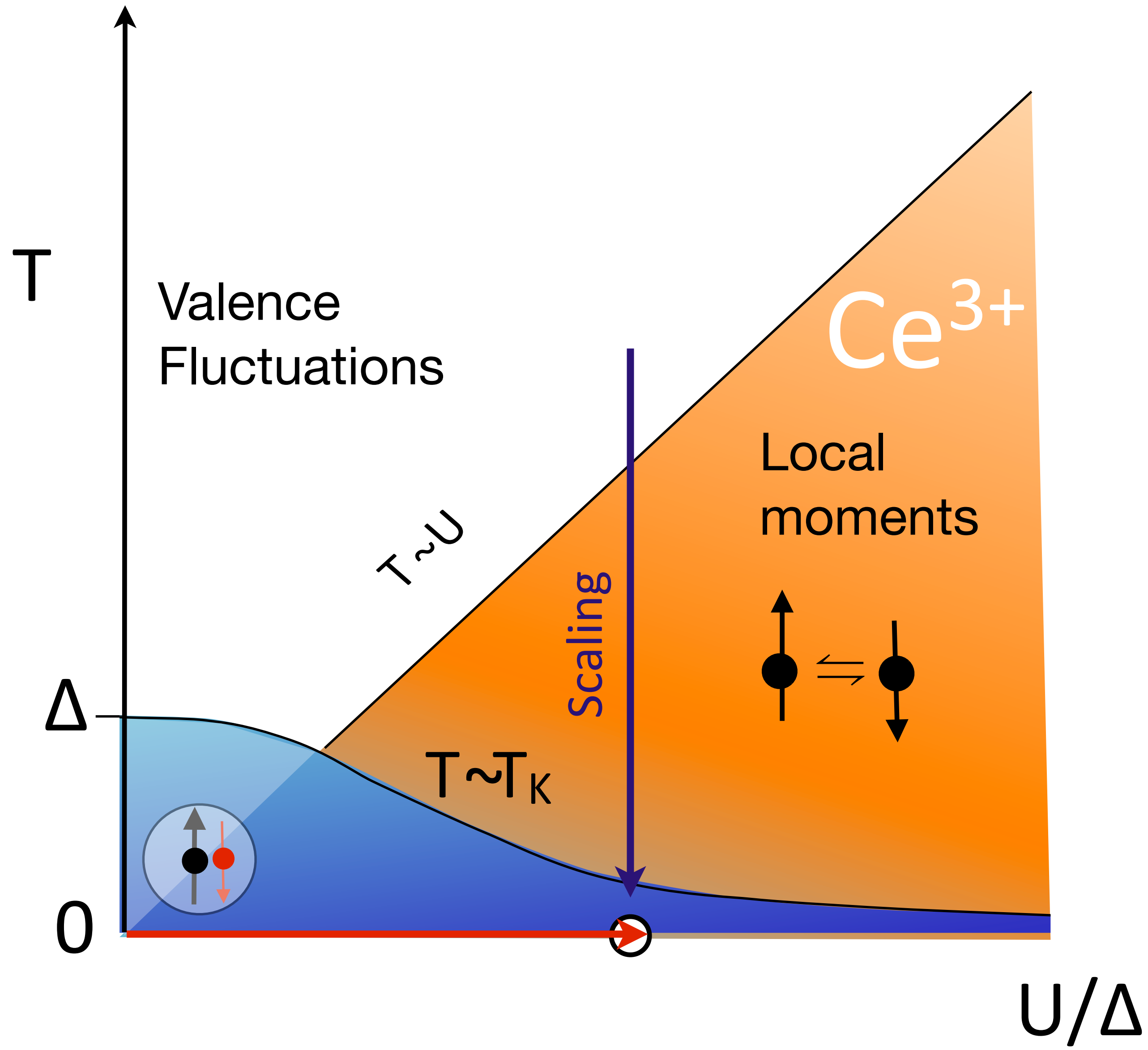
FIG. 2. Reciprocal molar susceptibility of SmB_6 as a function of temperature.

- Magnetic susceptibility flattens out below 100 K
- Renormalized band insulator?

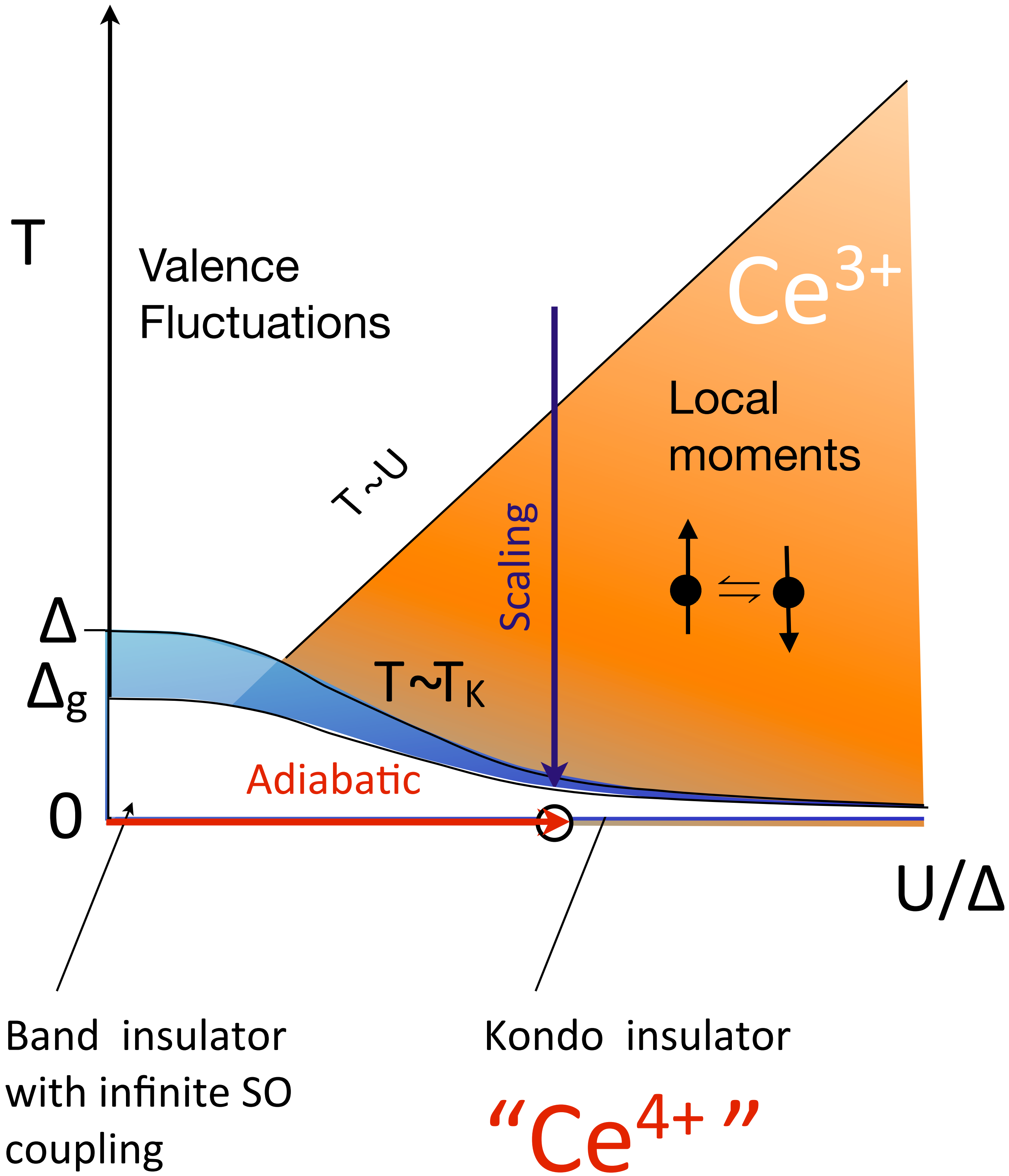
$$n_f \simeq 0.7$$

Neville Mott c. 1975



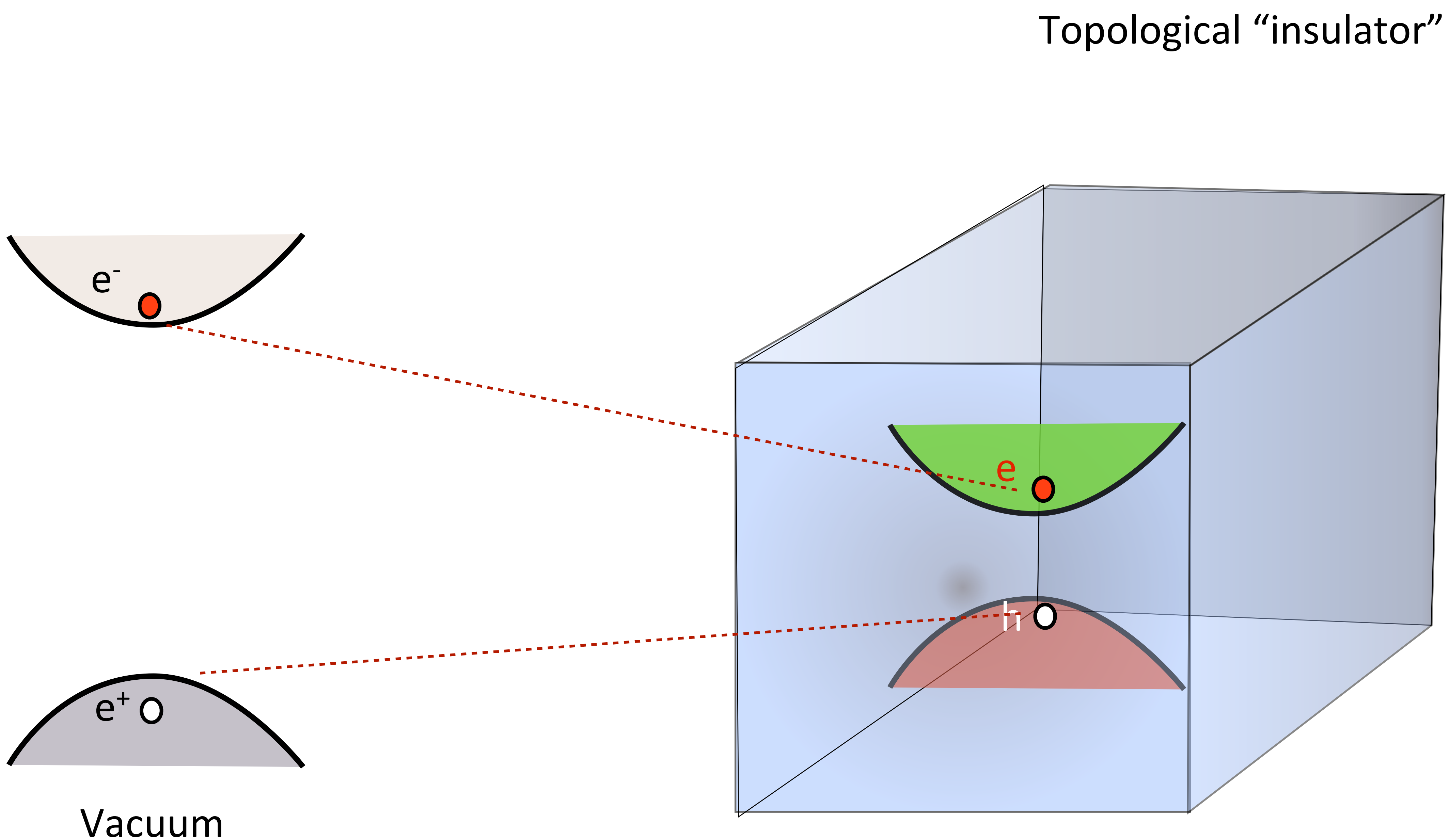


T
Valence
Fluctuations
Ce^{3+}
Local
moments
T ~U
Scaling
Δ
T ~T_K
0
U/Δ

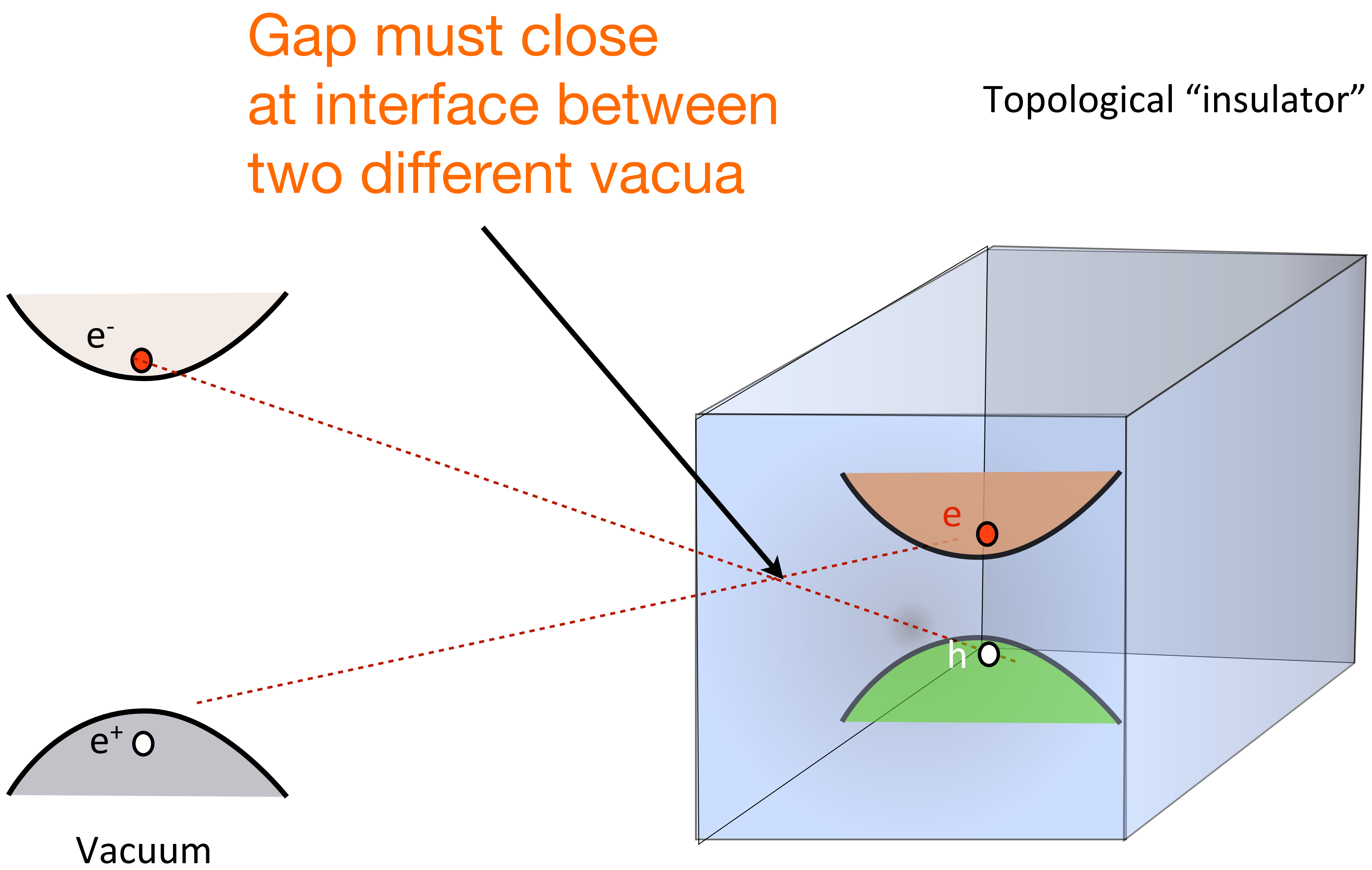


T
Valence Fluctuations
Ce^{3+}
Local moments
T~U
Scaling
Δ
Δ_g
$T \sim T_K$
Adiabatic
0
U/Δ
Band insulator with infinite SO coupling
Kondo insulator
"Ce^{4+}"

Topological insulator: adiabatically disconnected to vacuum.



Topological insulator: adiabatically disconnected to vacuum.



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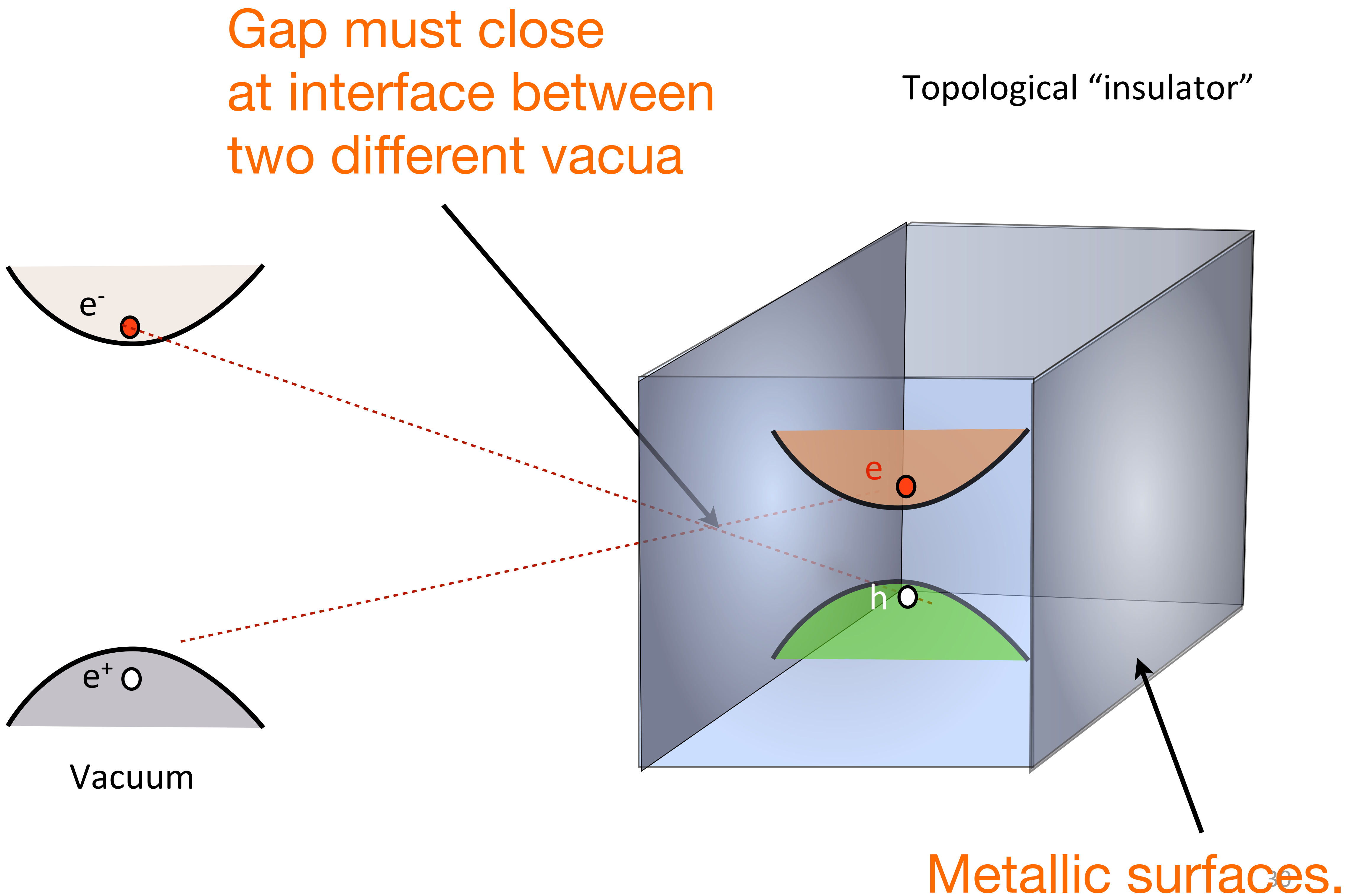
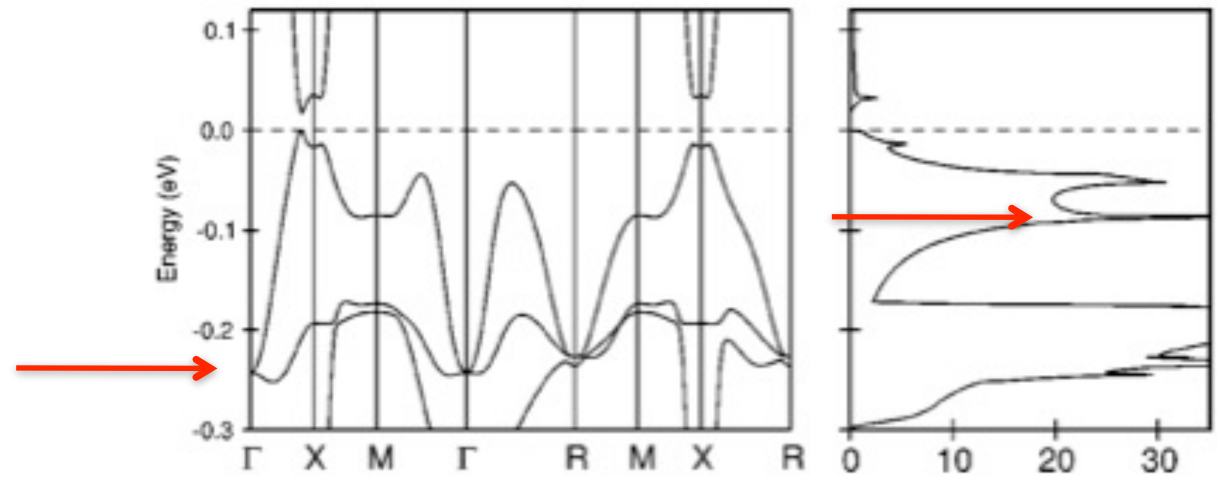
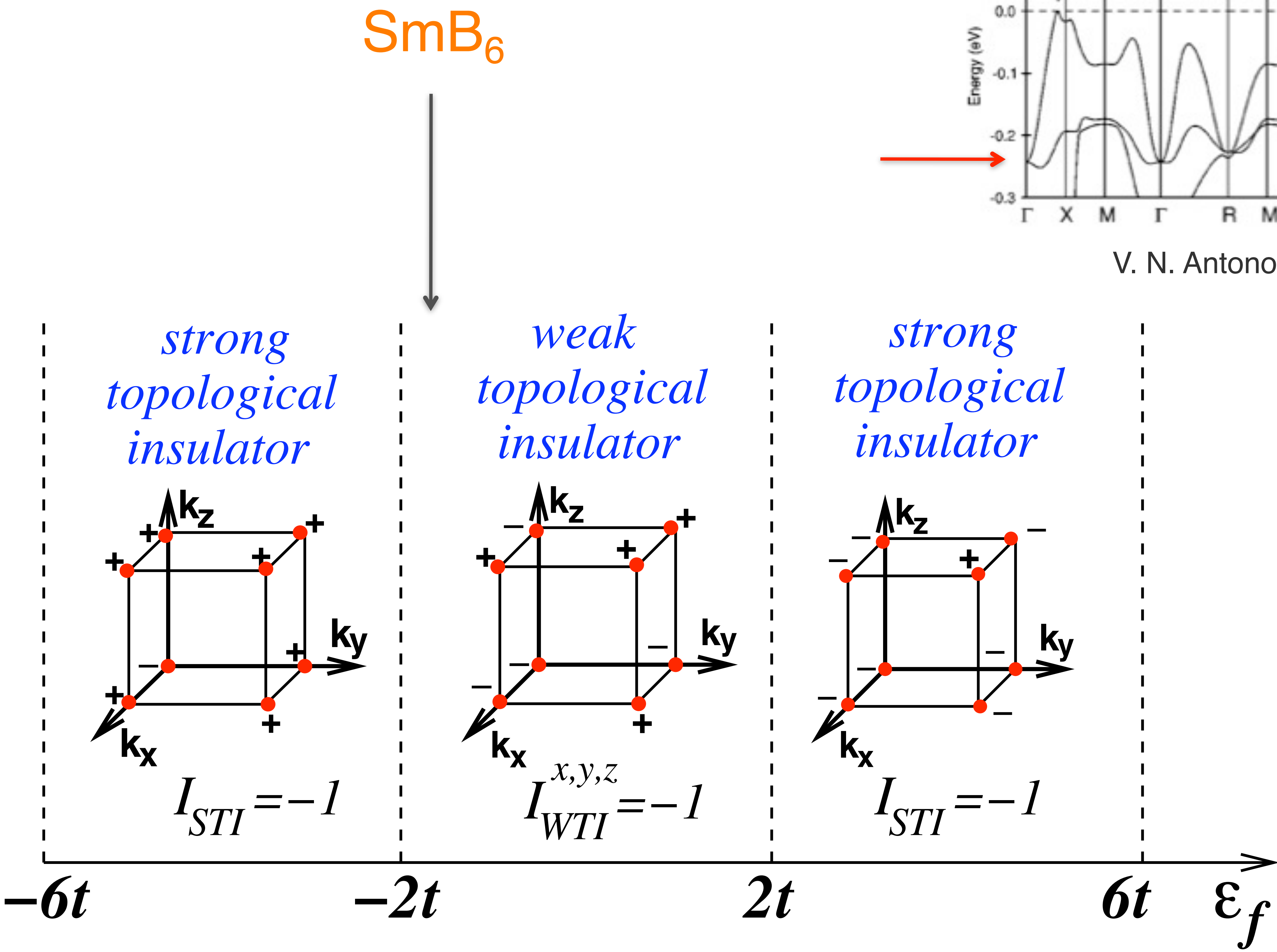


Are existing Kondo insulators weak or strong TI?



V. N. Antonov et al. PRB (2006)



Aline Ramires Rutgers
Andriy Nevidomskyy Rice
Satoru Nakatsuji Tokyo
Yosuke Matsumoto Tokyo
Alexei Tsvelik Brookhaven


Aline


Satoru


Yosuke


Alexei

YbAlB4: a possible vortex metal.

S. NAKATSUJI[1]*, K. KUGA[1,2], Y. MACHIDA[1], T. TAYAMA[1], T. SAKAKIBARA[1], Y. KARAKI[1], H. ISHIMOTO[1], S. YONEZAWA[2], Y. MAENO[2], E. PEARSON[3], G. G. LONZARICH[3], L. BALICAS[4], H. LEE[4†] AND Z. FISK[5]

Nature Physics, 603, (2008)

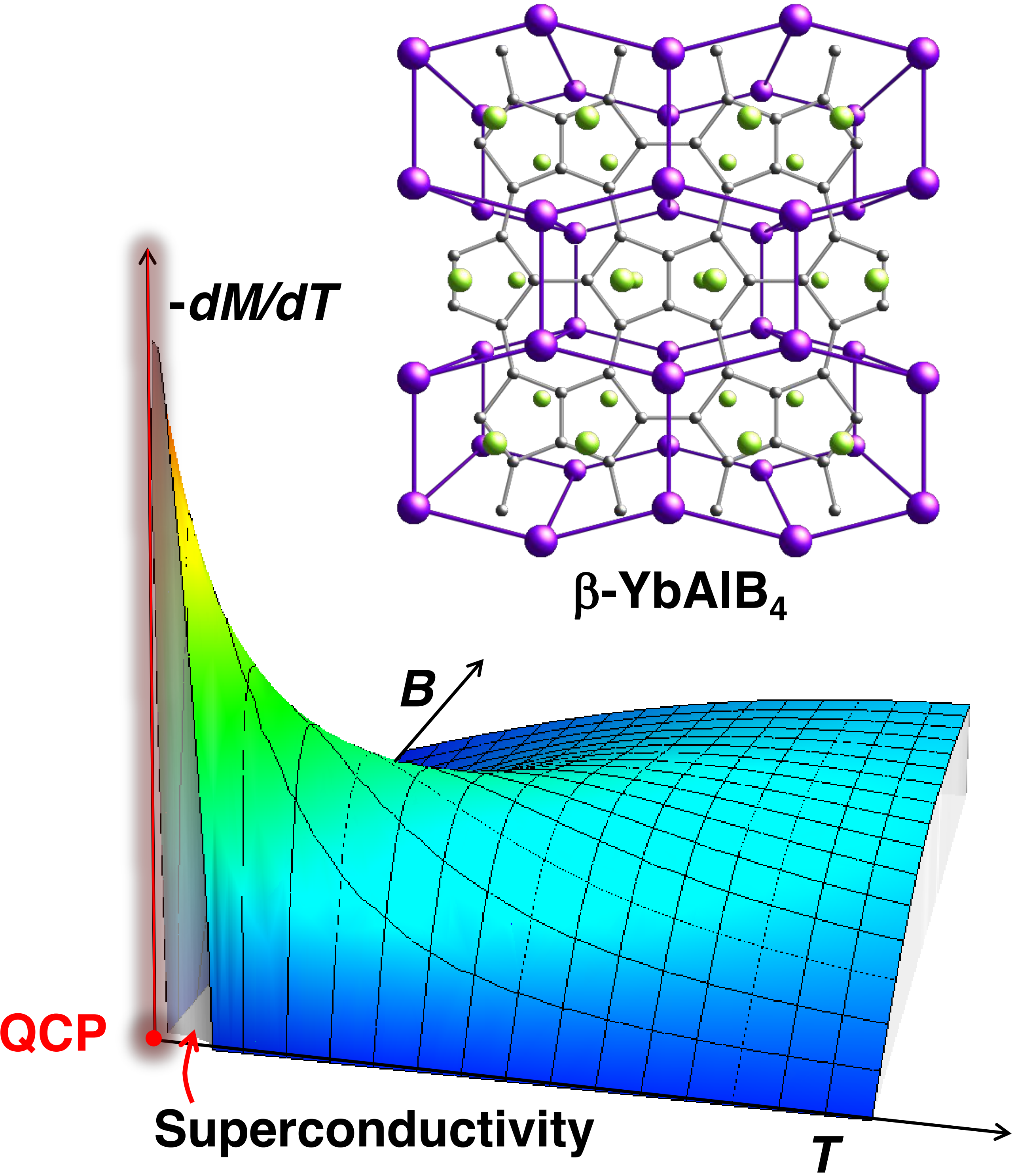
Andriy Nevidomskyy and P.C, Phys. Rev. Lett., 102, 077202 (2009)

Quantum Criticality Without Tuning in the Mixed Valence Compound β-$YbAlB_4$

Yosuke Matsumoto,[1] Satoru Nakatsuji,[1]* Kentaro Kuga,[1] Yoshitomo Karaki,[1]† Naoki Horie,[1] Yasuyuki Shimura,[1] Toshiro Sakakibara,[1] Andriy H. Nevidomskyy,[2,3] Piers Coleman[2,4]*

Science, 331, 316 (2011)

Mystery IV: $YbAlB_4$



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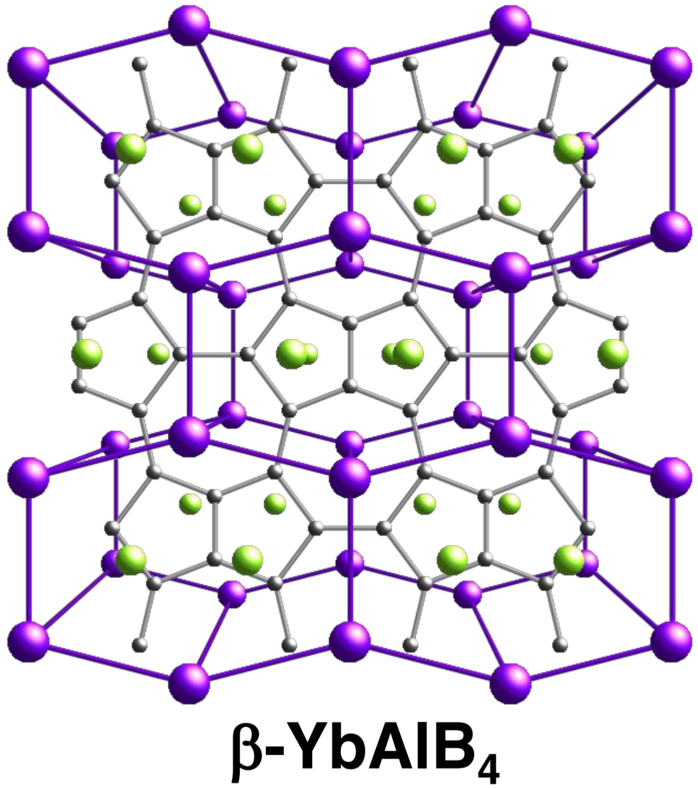
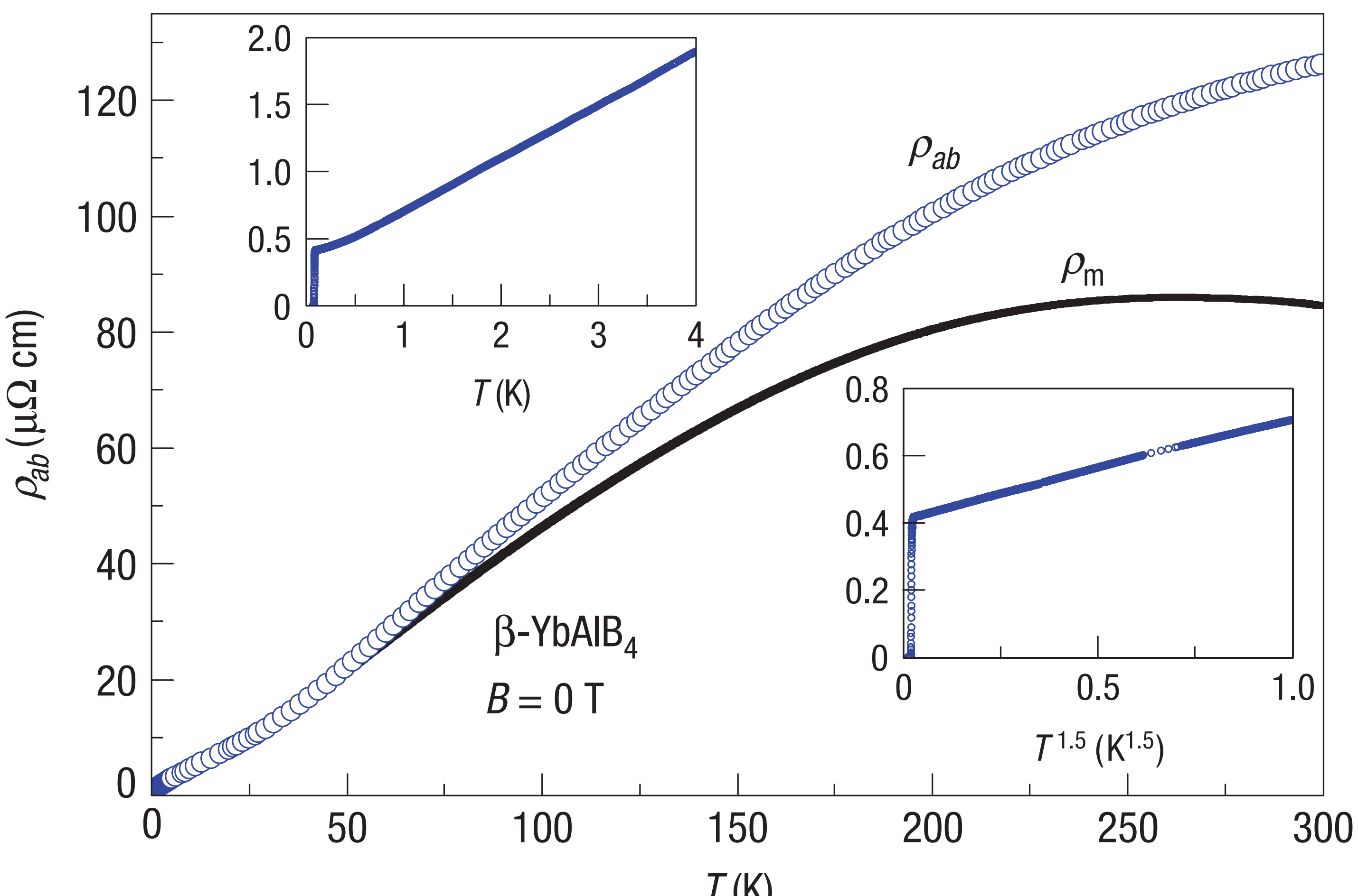
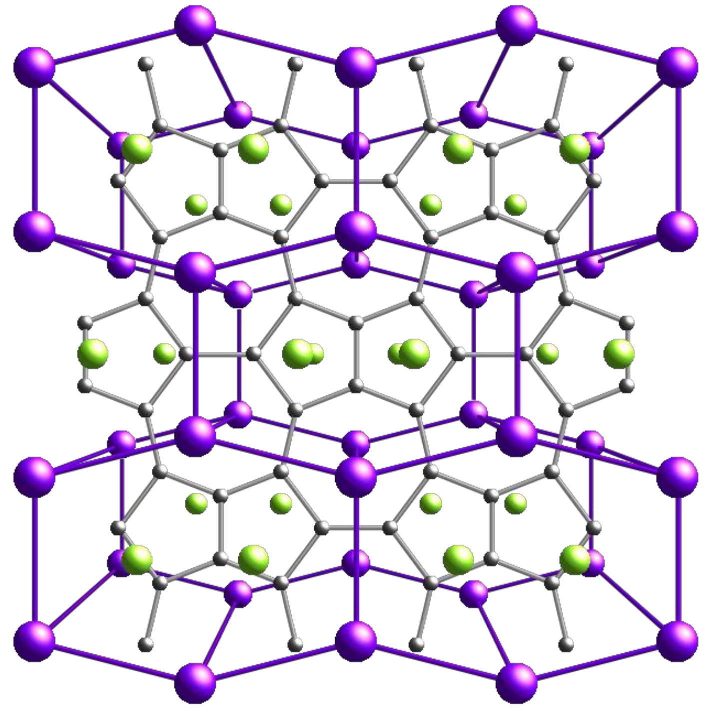


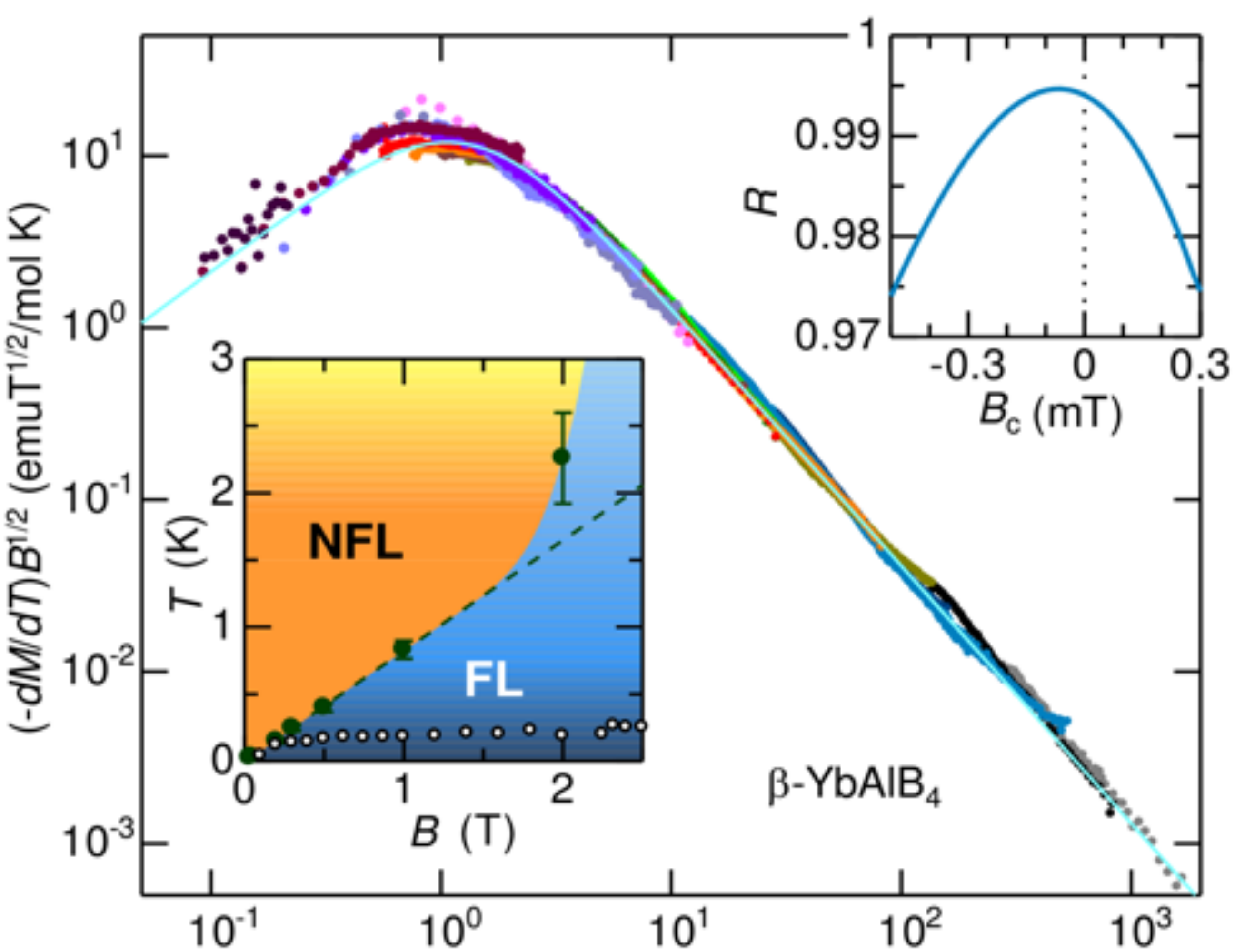


Mystery IV: $YbAlB_4$

"Intrinsically quantum critical"



β-$YbAlB_4$



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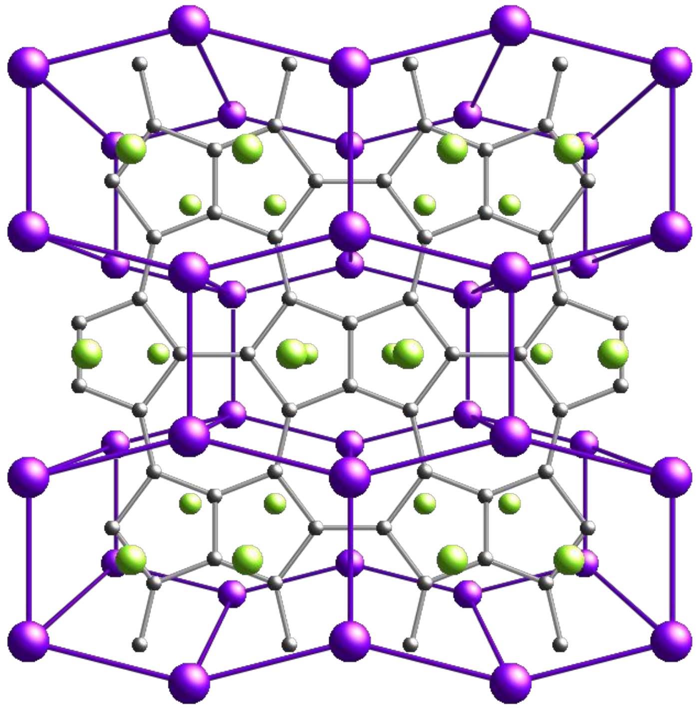
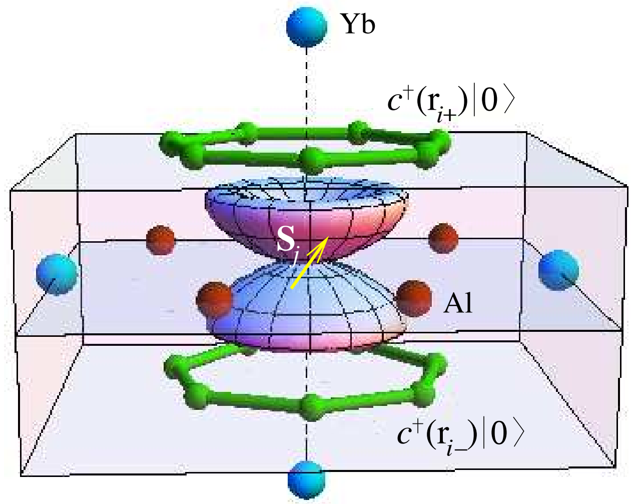
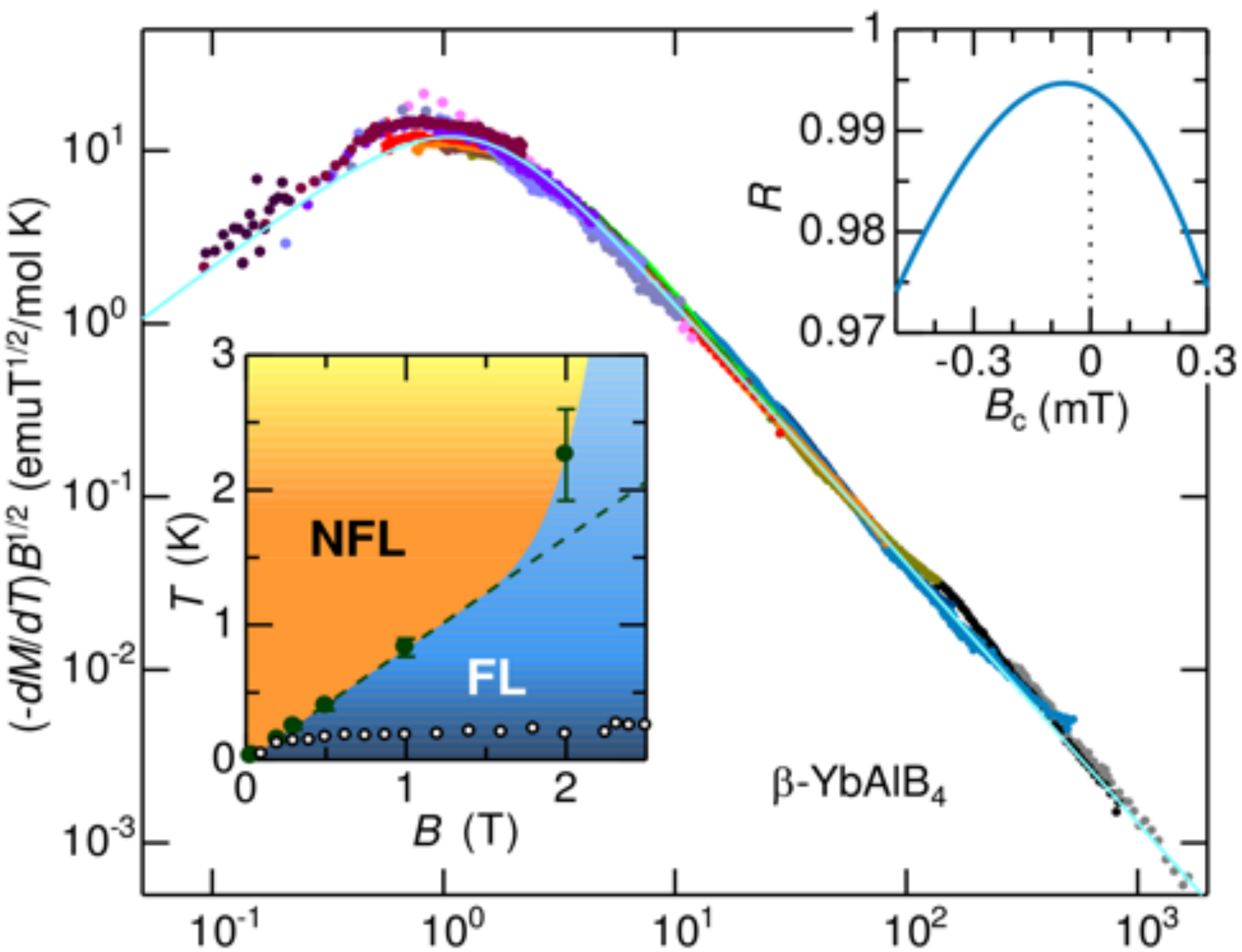
Nevidomskyy and Coleman (08)







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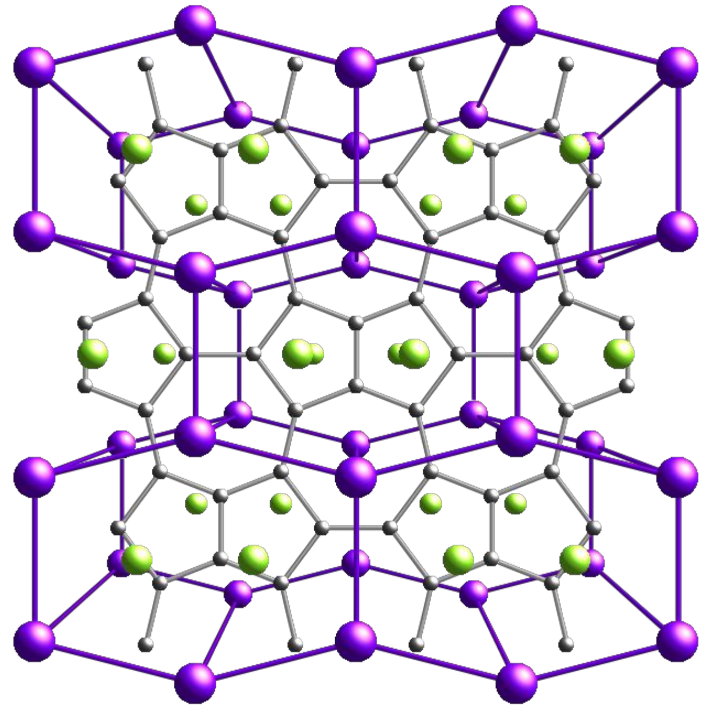

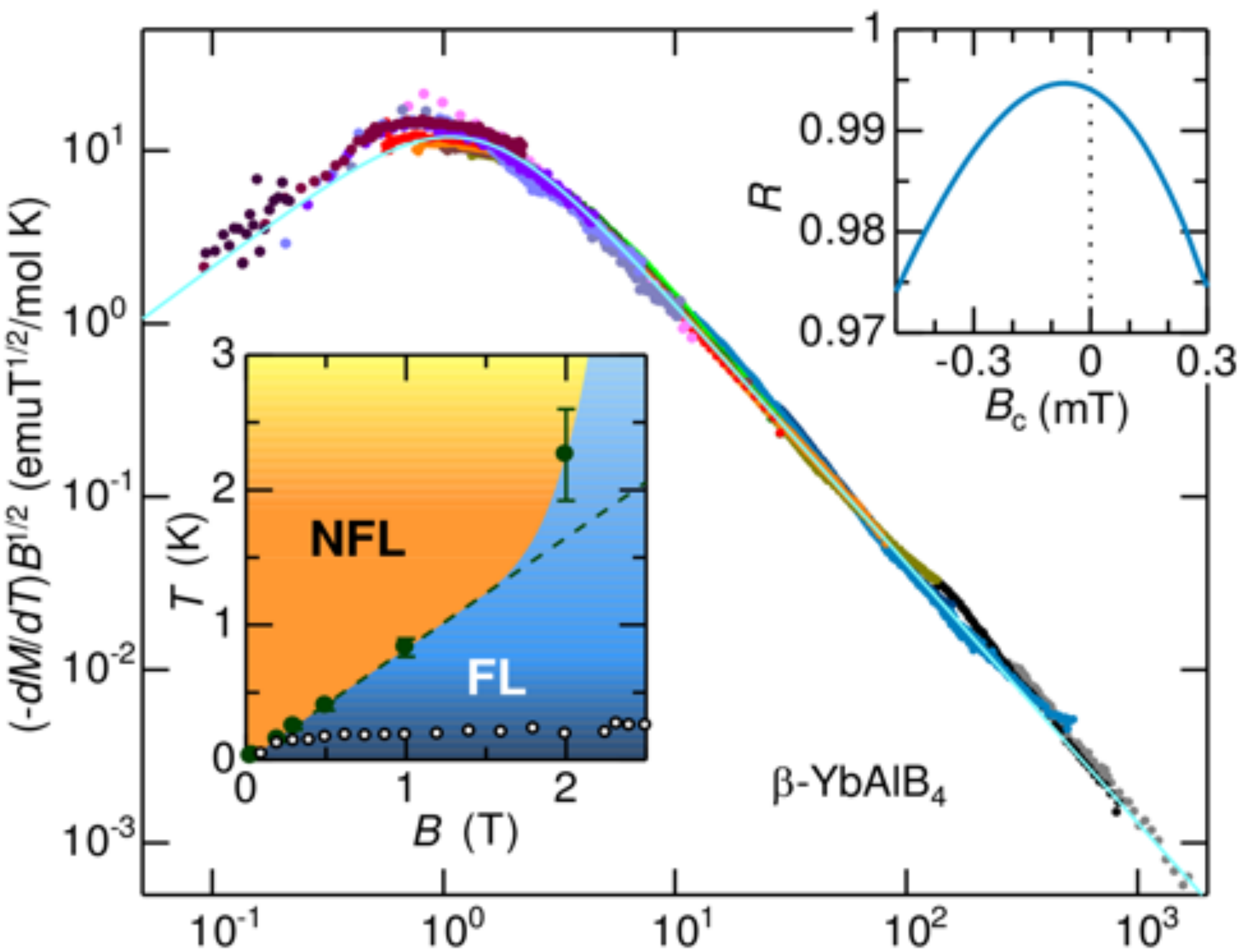

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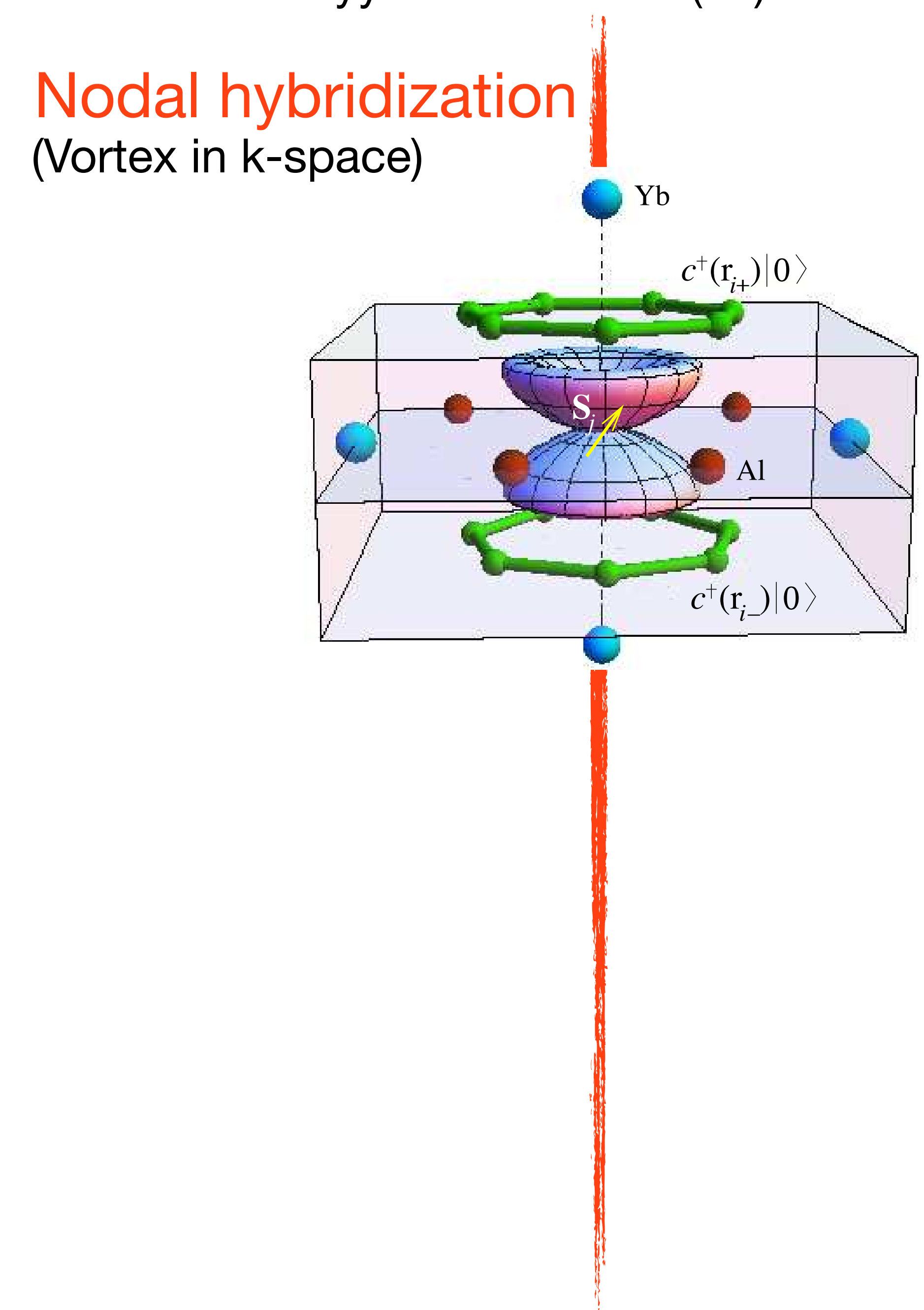
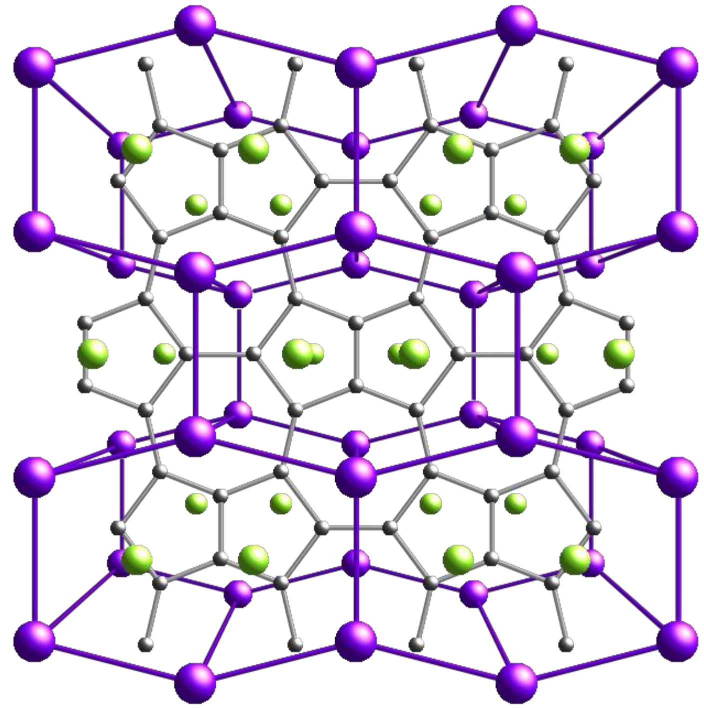
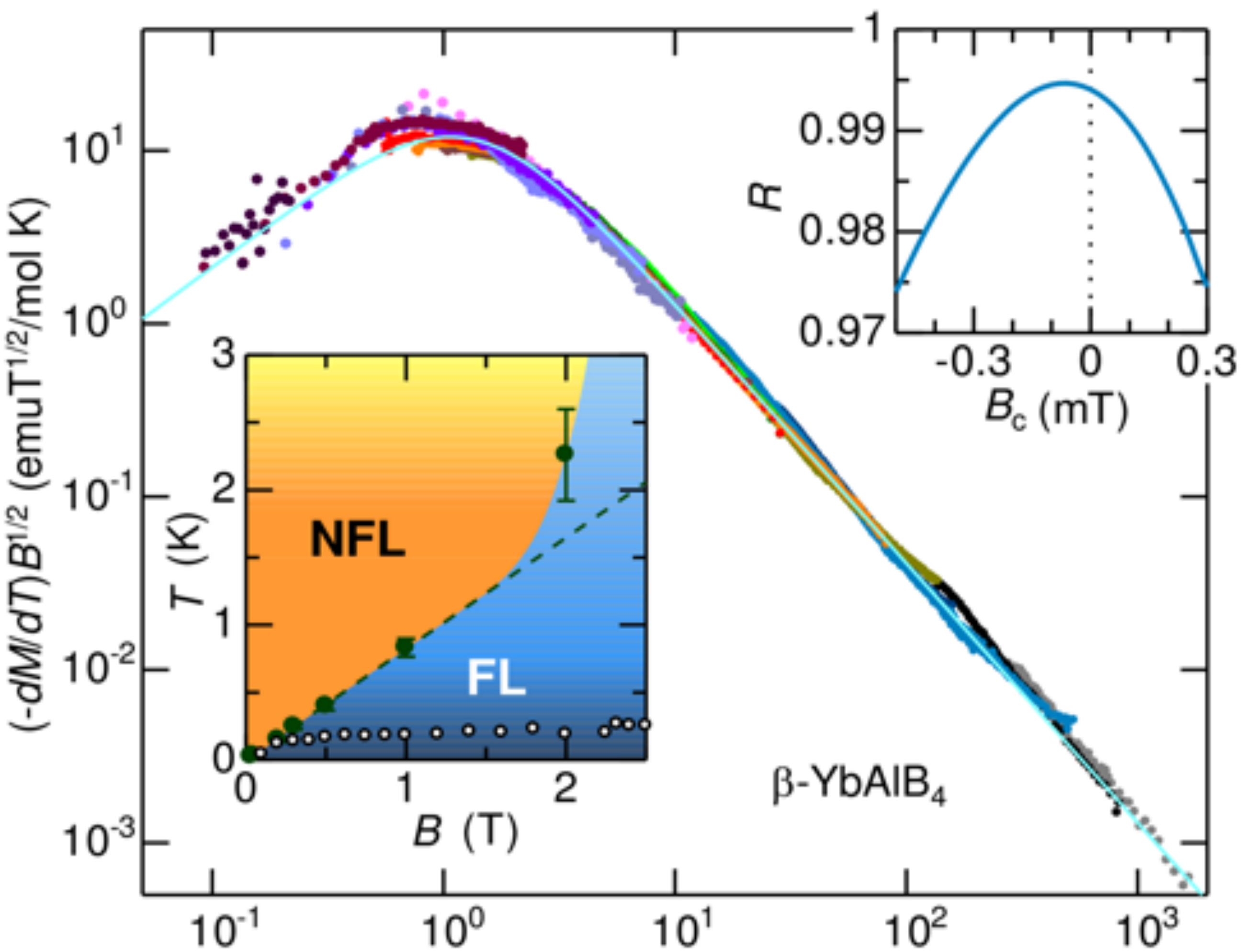


Mystery IV: $YbAlB_4$

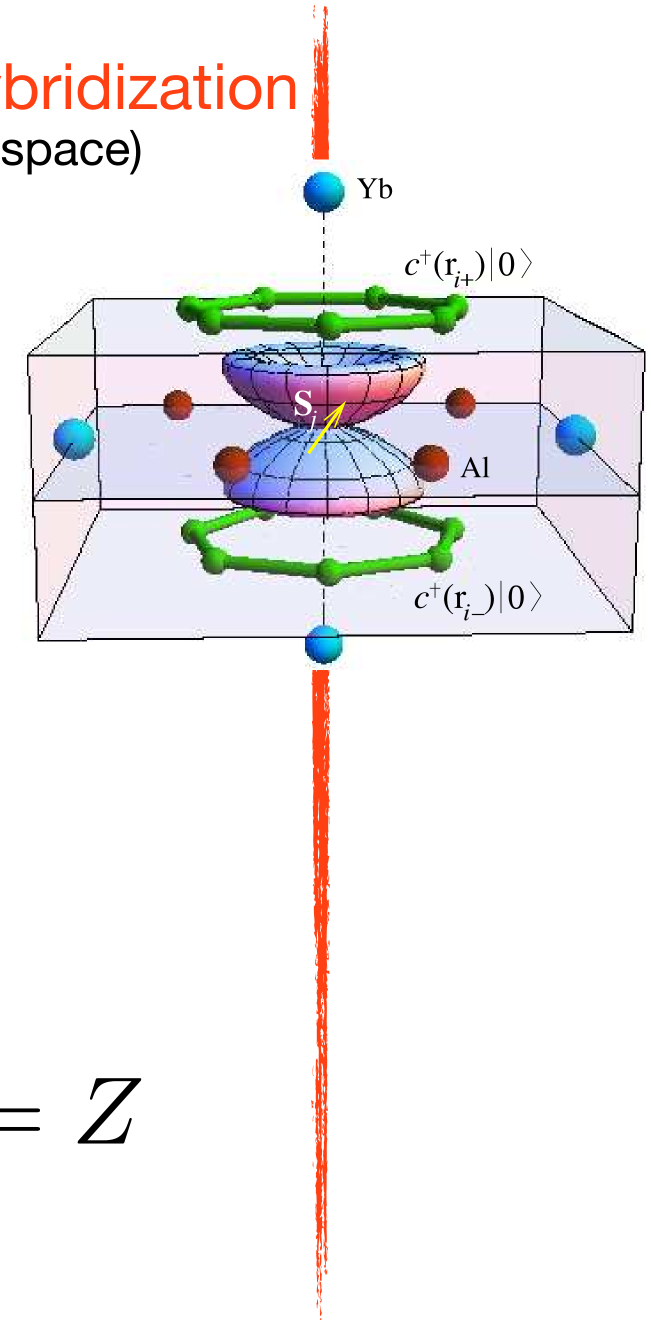
"Intrinsically quantum critical"





Nevidomskyy and Coleman (08)

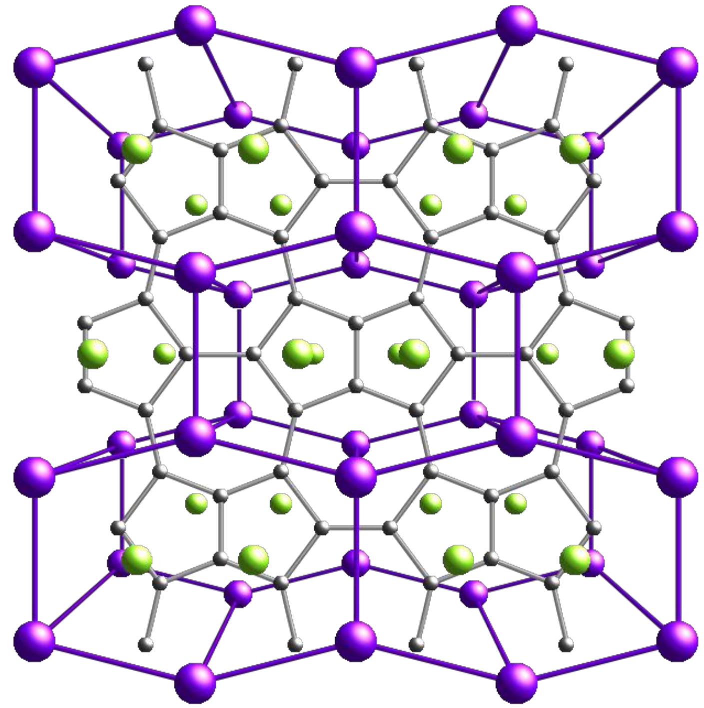
Nodal hybridization
(Vortex in k-space)



$$\pi_1[h] = Z$$

Mystery IV: $YbAlB_4$

“Intrinsically quantum critical”



β-$YbAlB_4$

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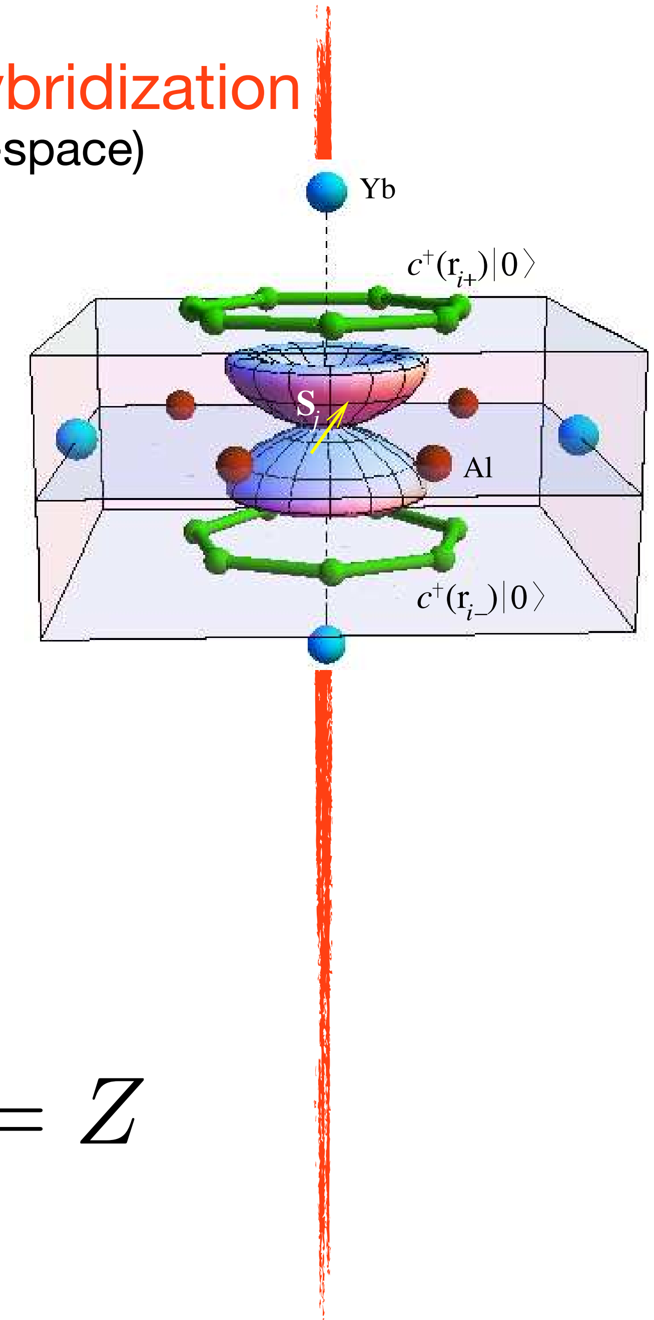

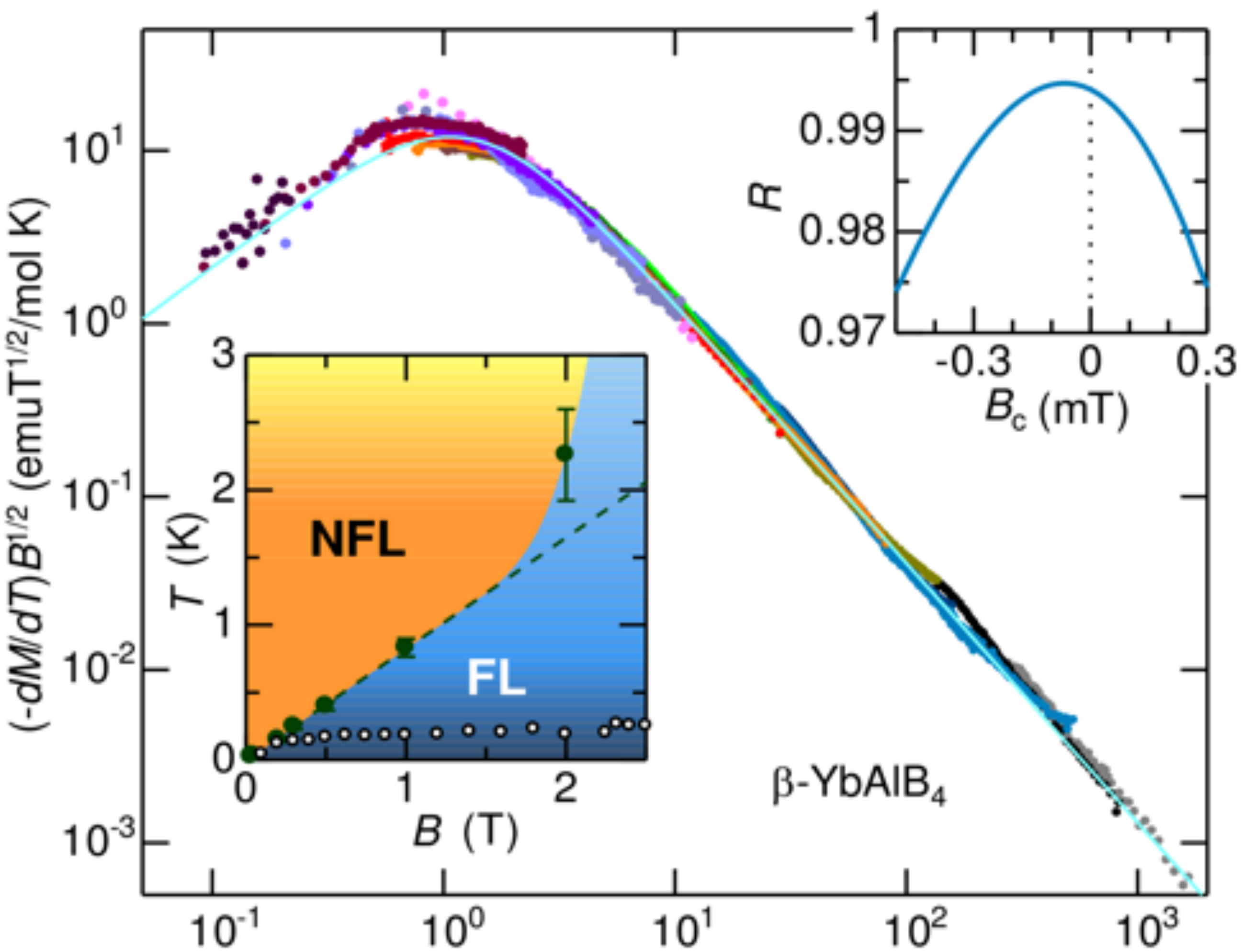

$$\pi_1[h] = Z$$

$$|V(k)|^2 \propto |(k_x + ik_y)^4|$$

Tsvelik, Coleman & Ramires (2012)

Mystery IV: $YbAlB_4$

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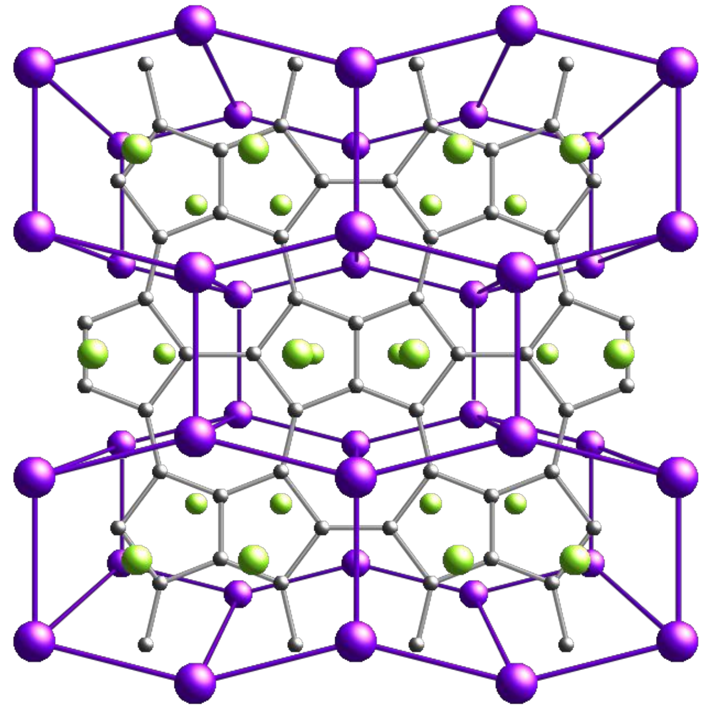

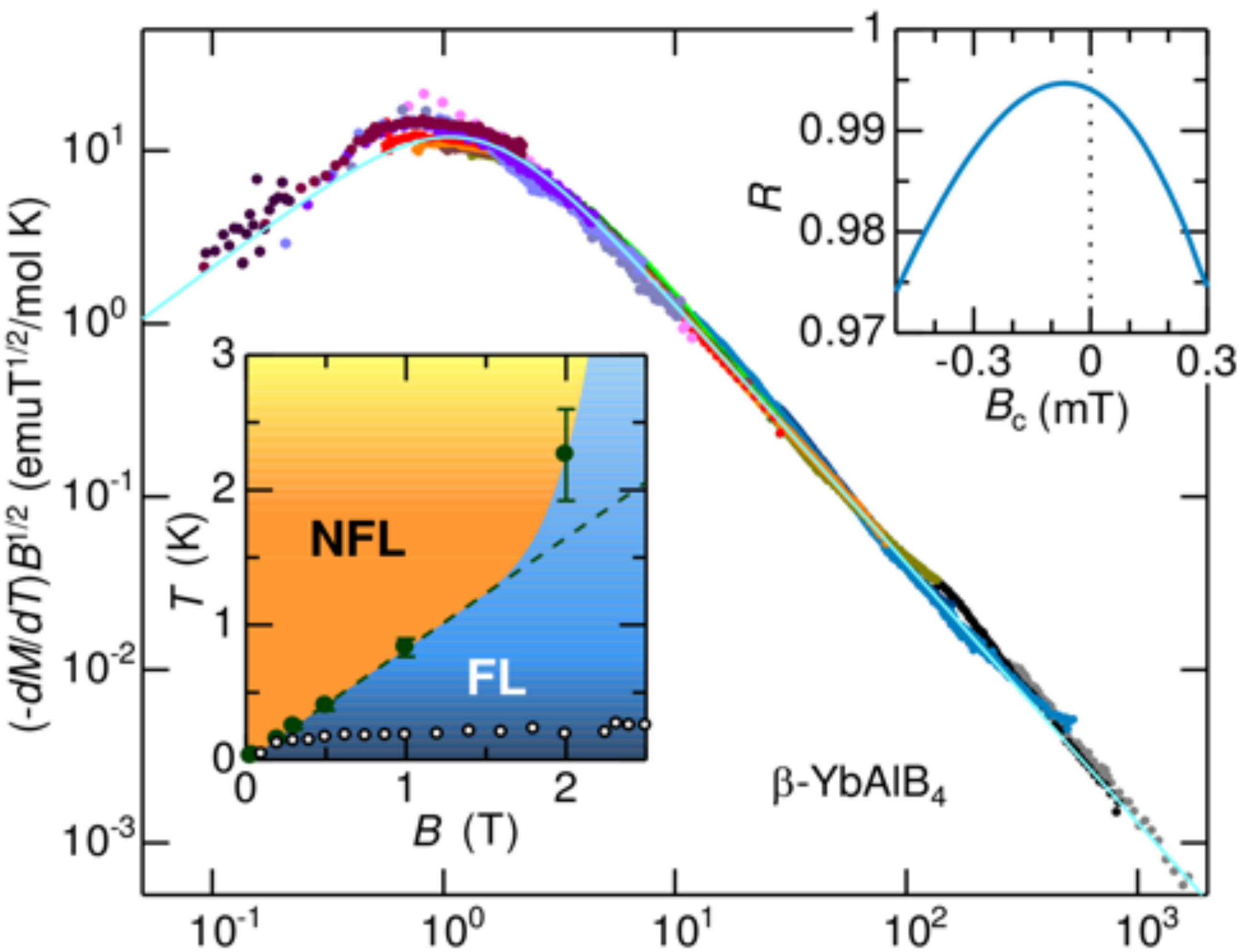

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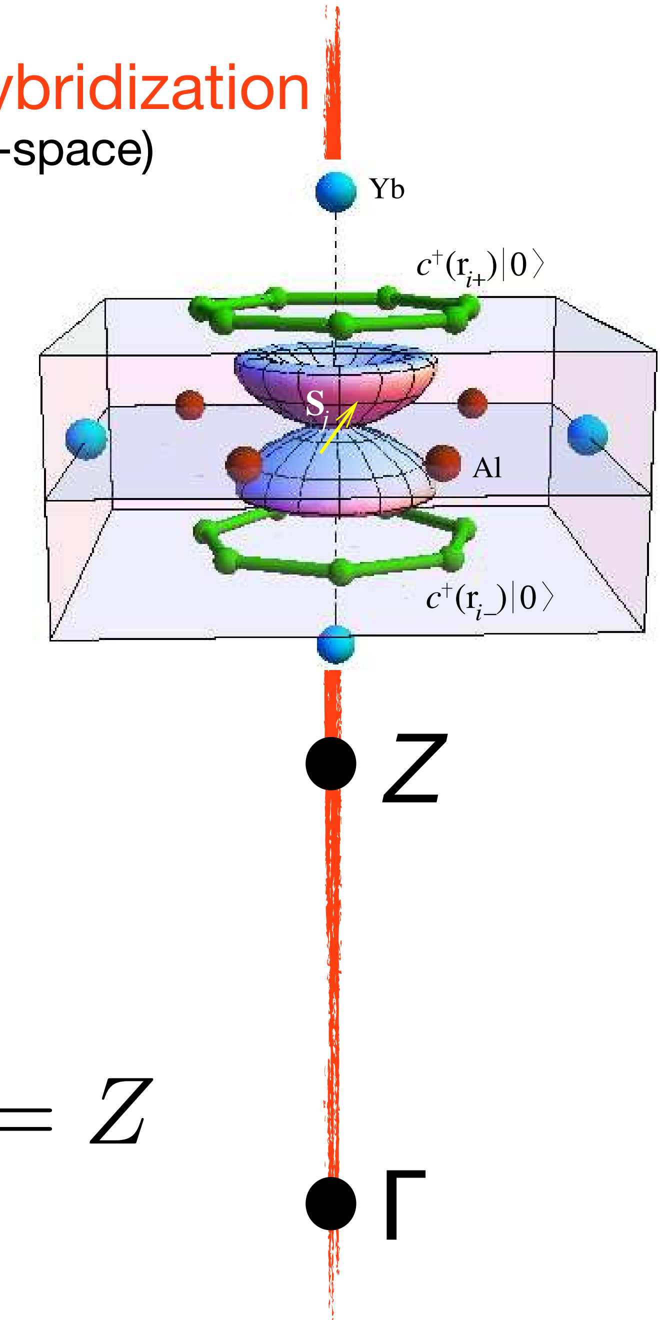

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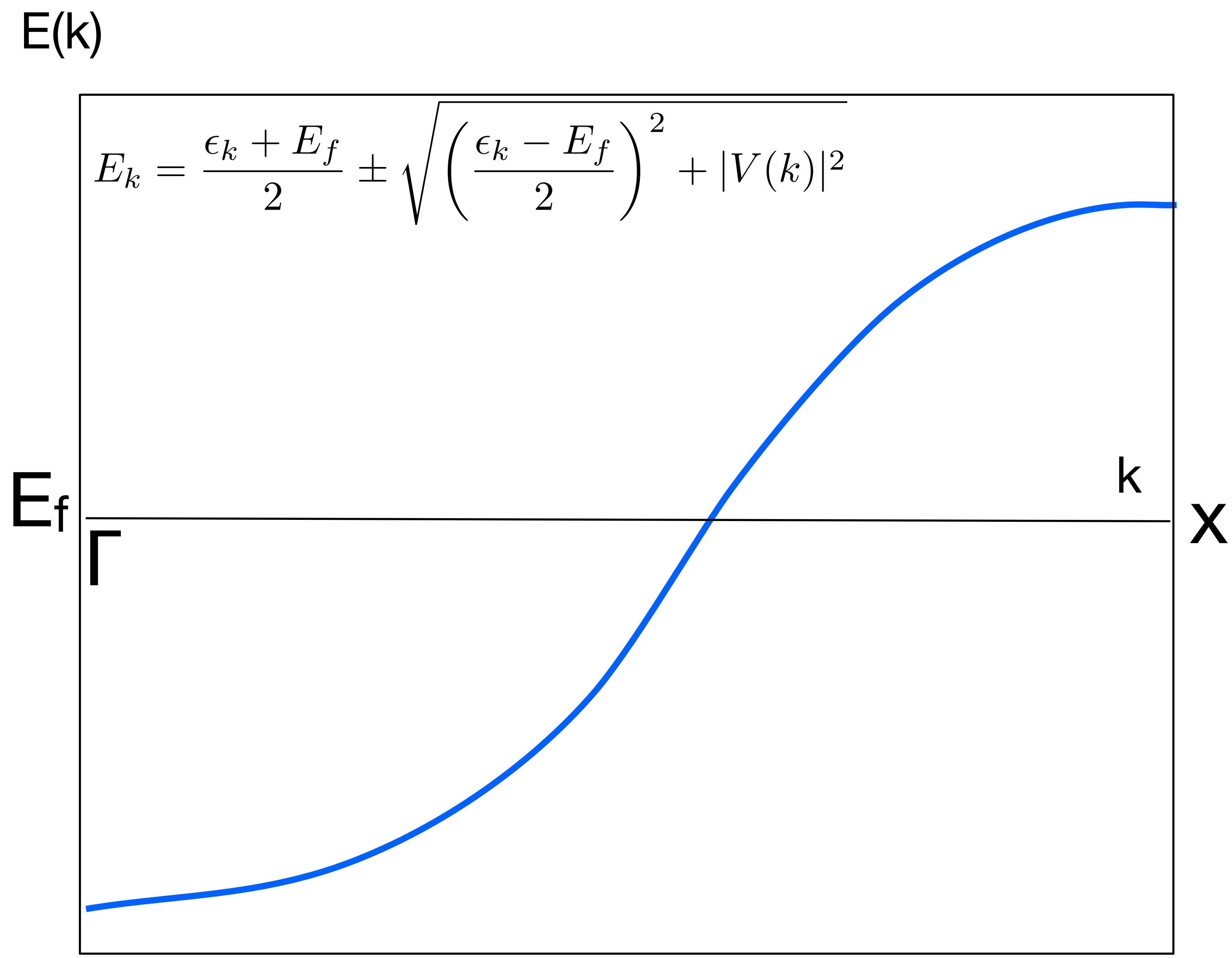
Tsvelik, Coleman & Ramires (2012)

$$E_k = \frac{\epsilon_k + E_f}{2} \pm \sqrt{\left(\frac{\epsilon_k - E_f}{2}\right)^2 + |V(k)|^2}$$



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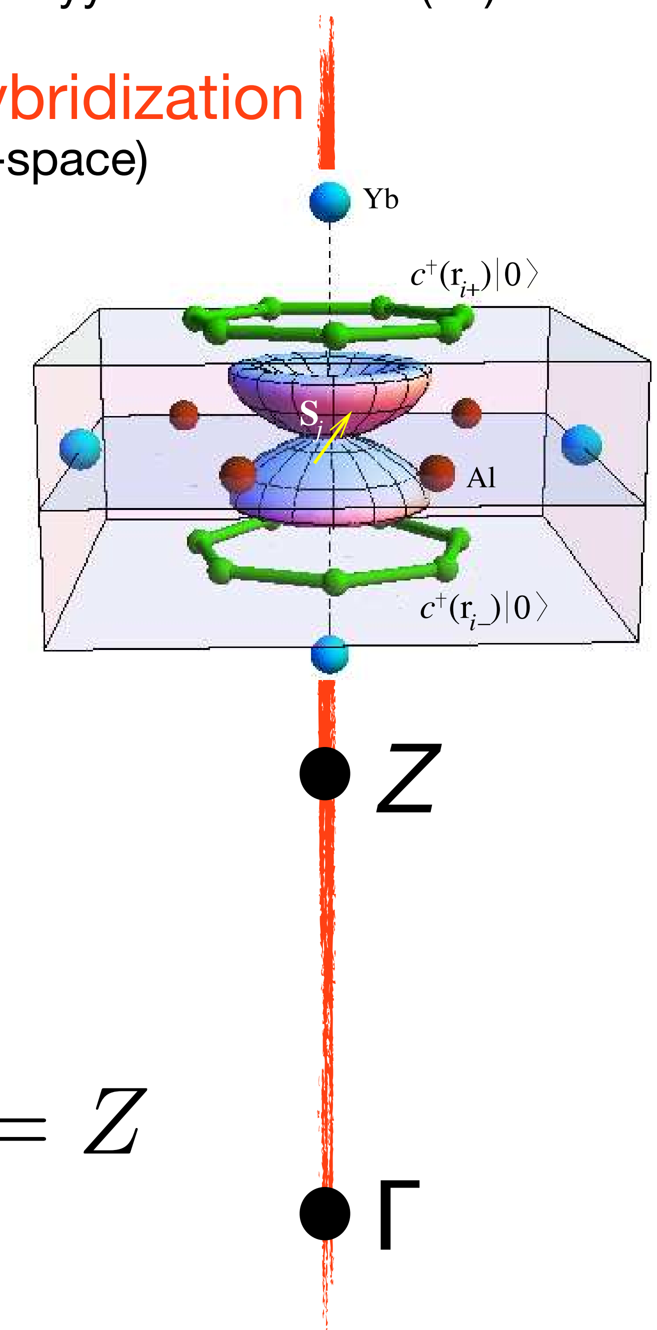

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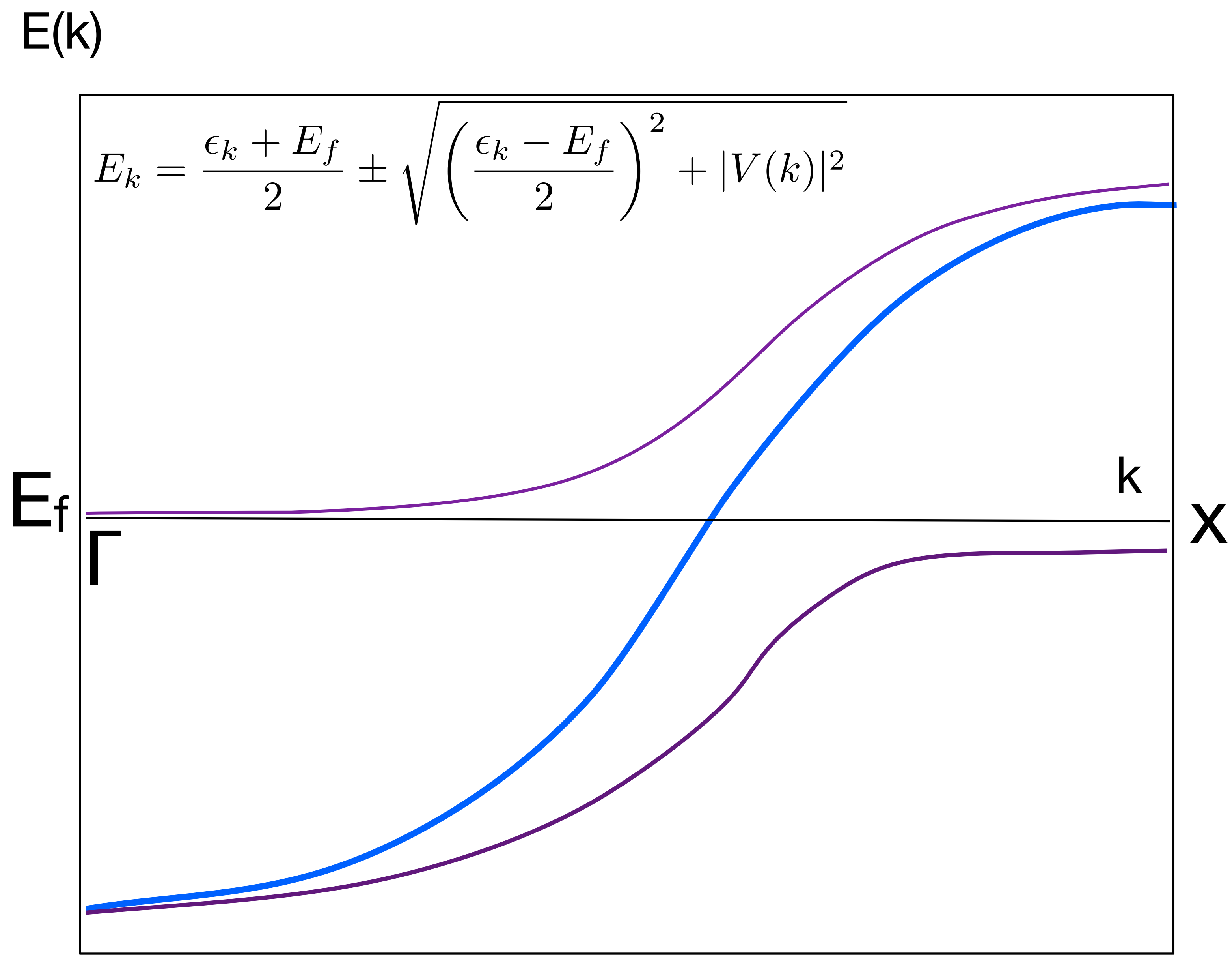

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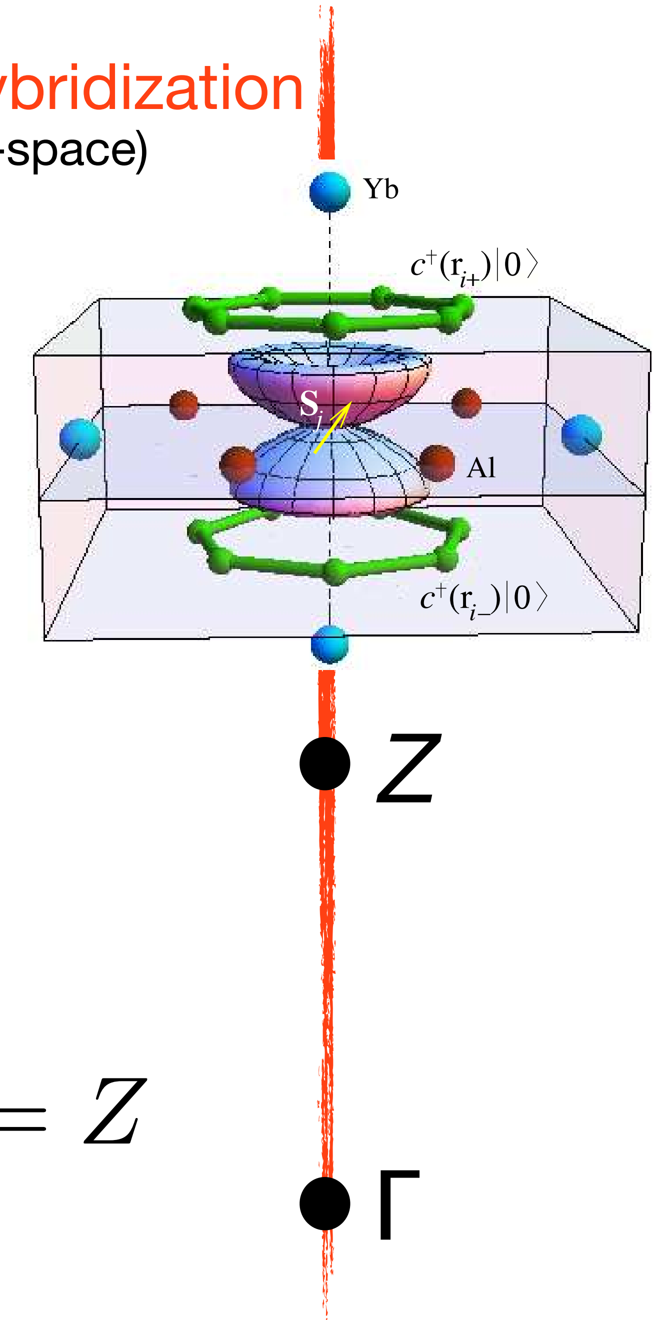

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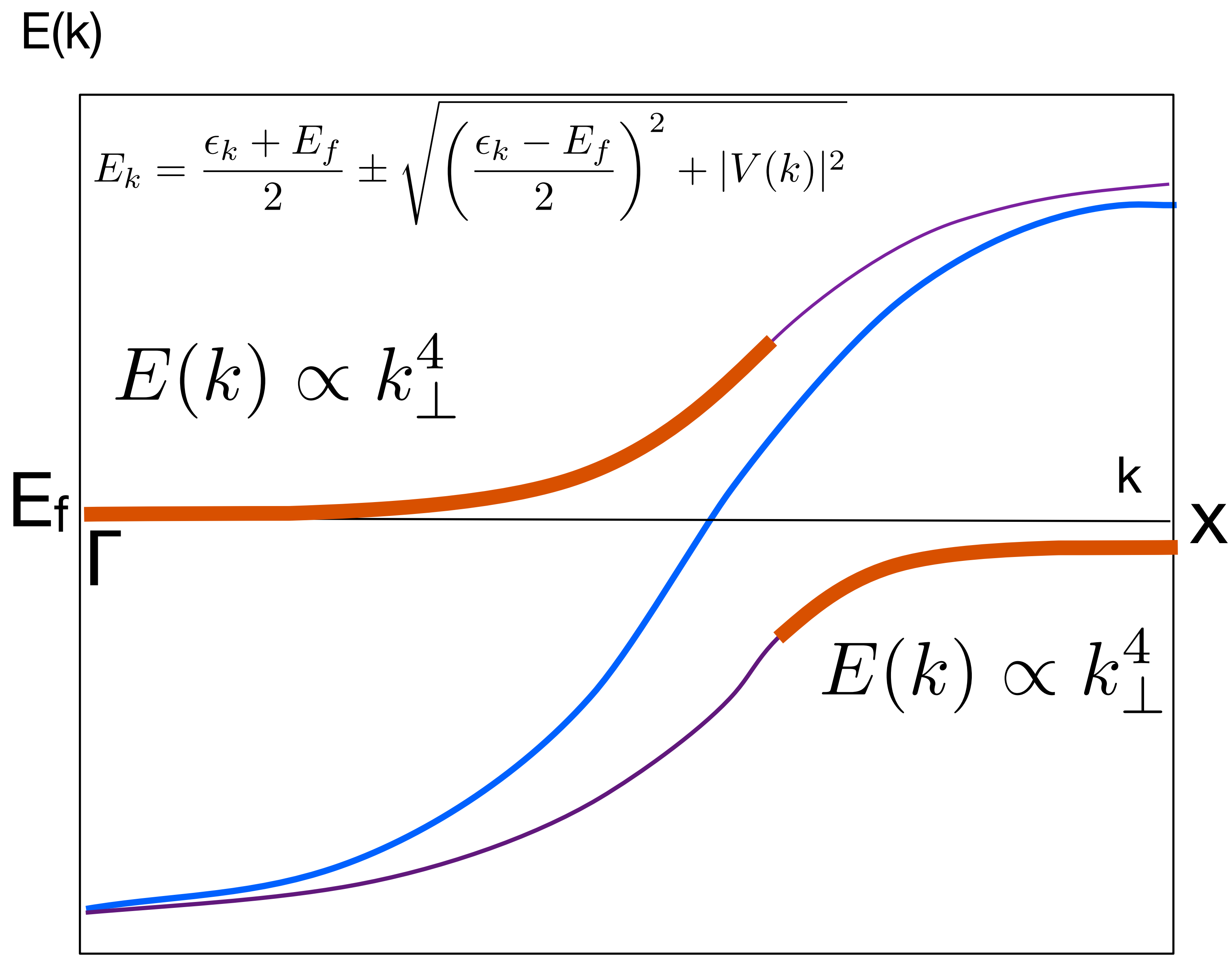
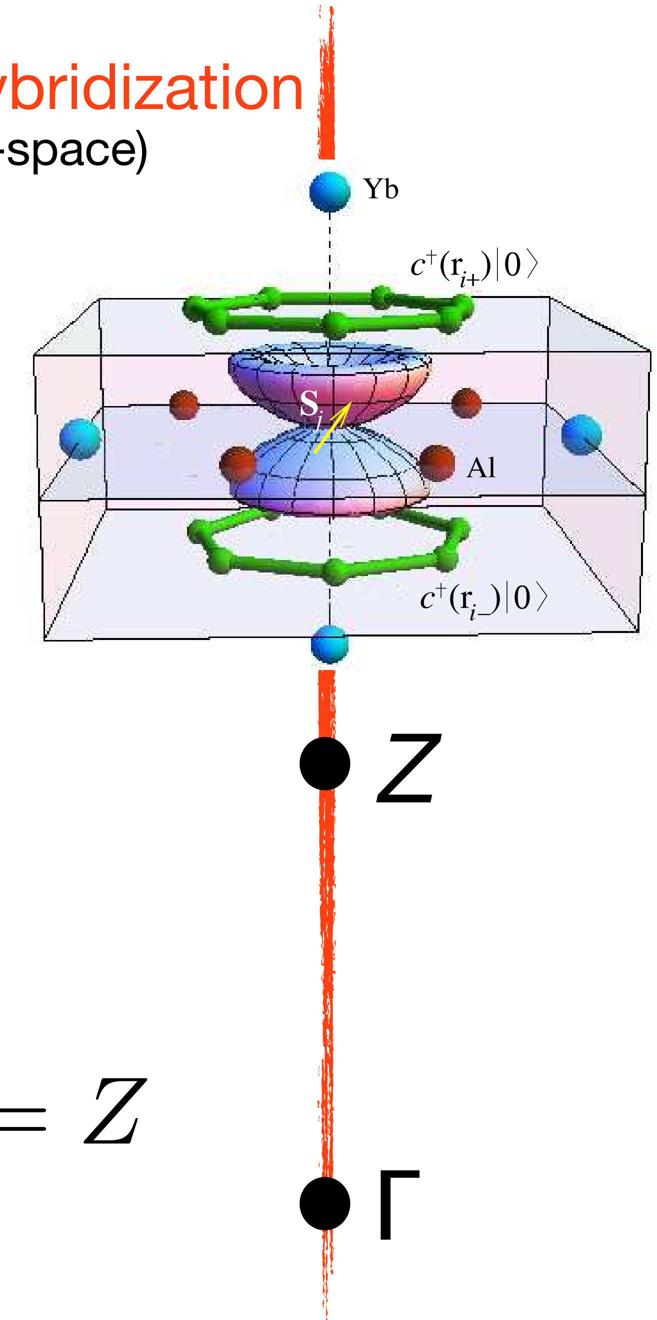


Nevidomskyy and Coleman (08)

Nodal hybridization
(Vortex in k-space)



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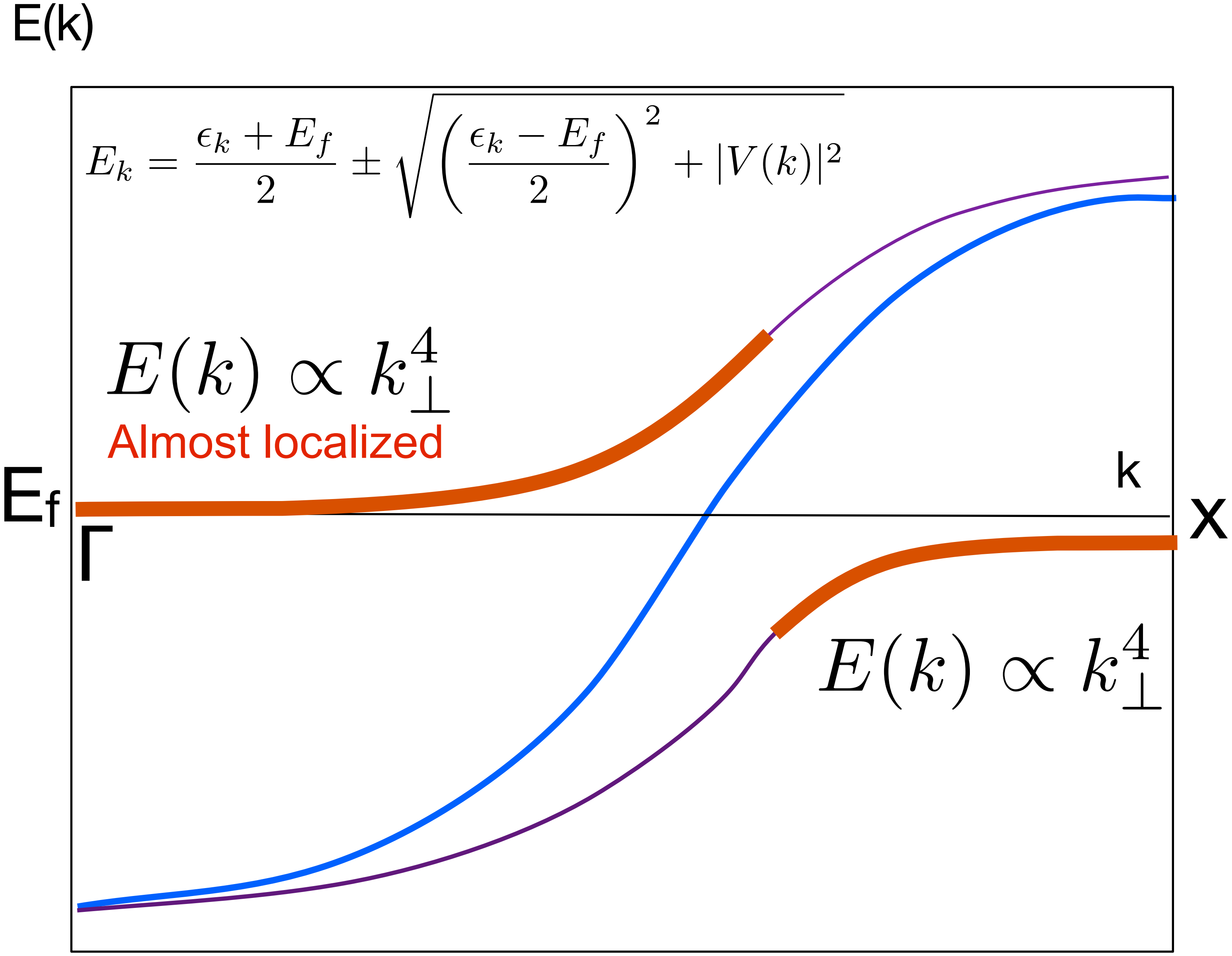

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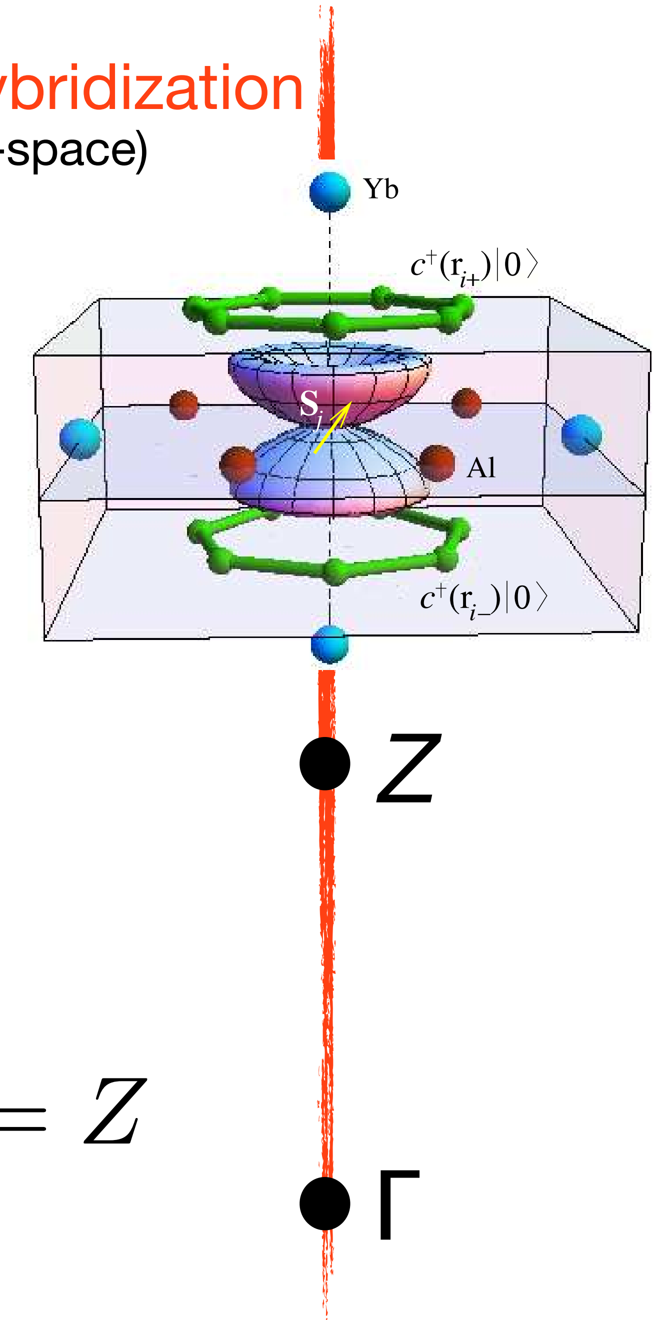

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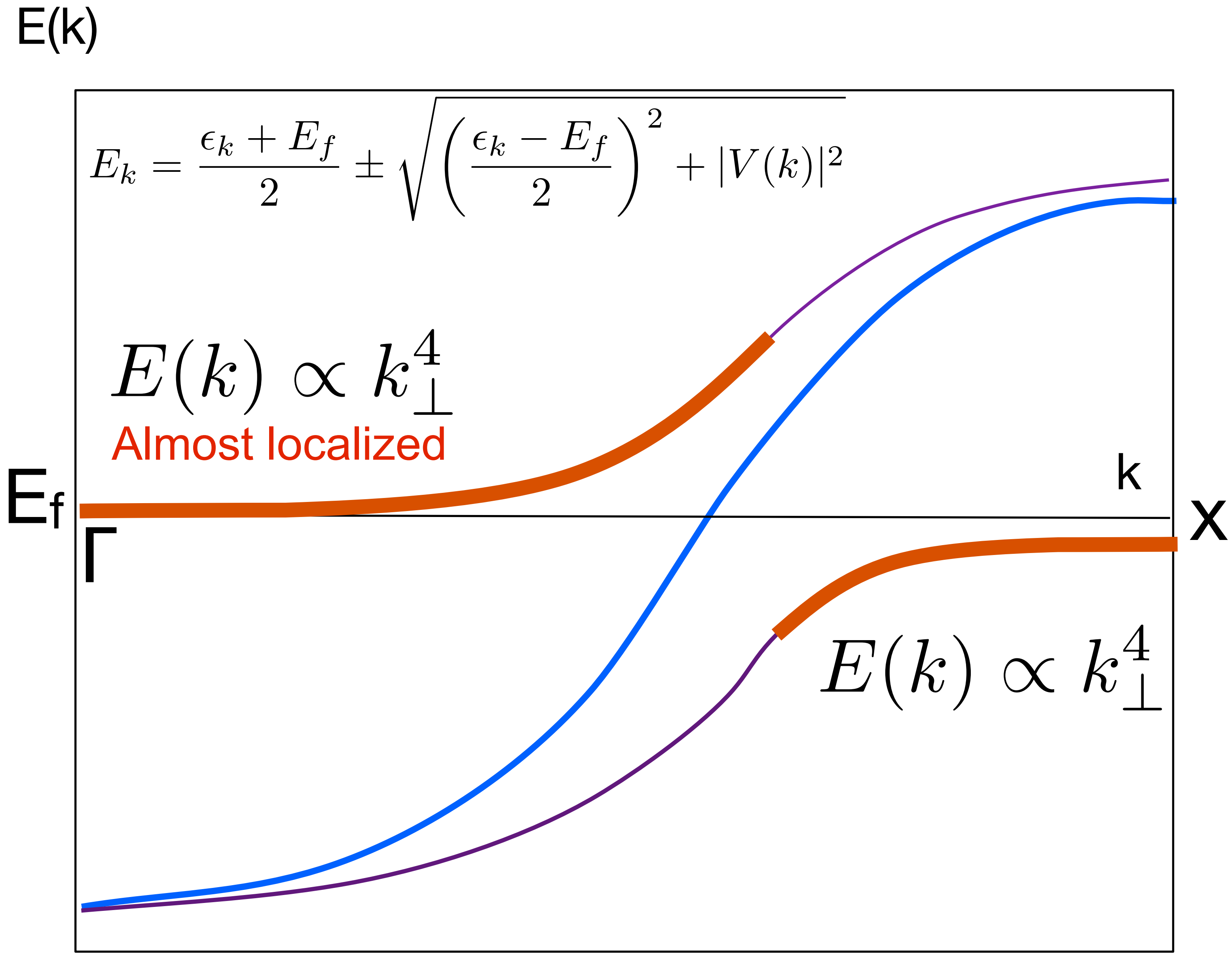

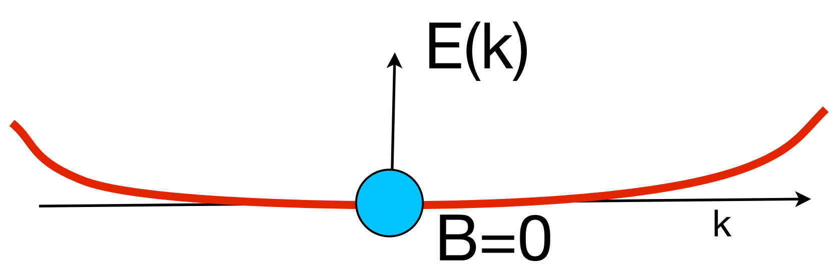

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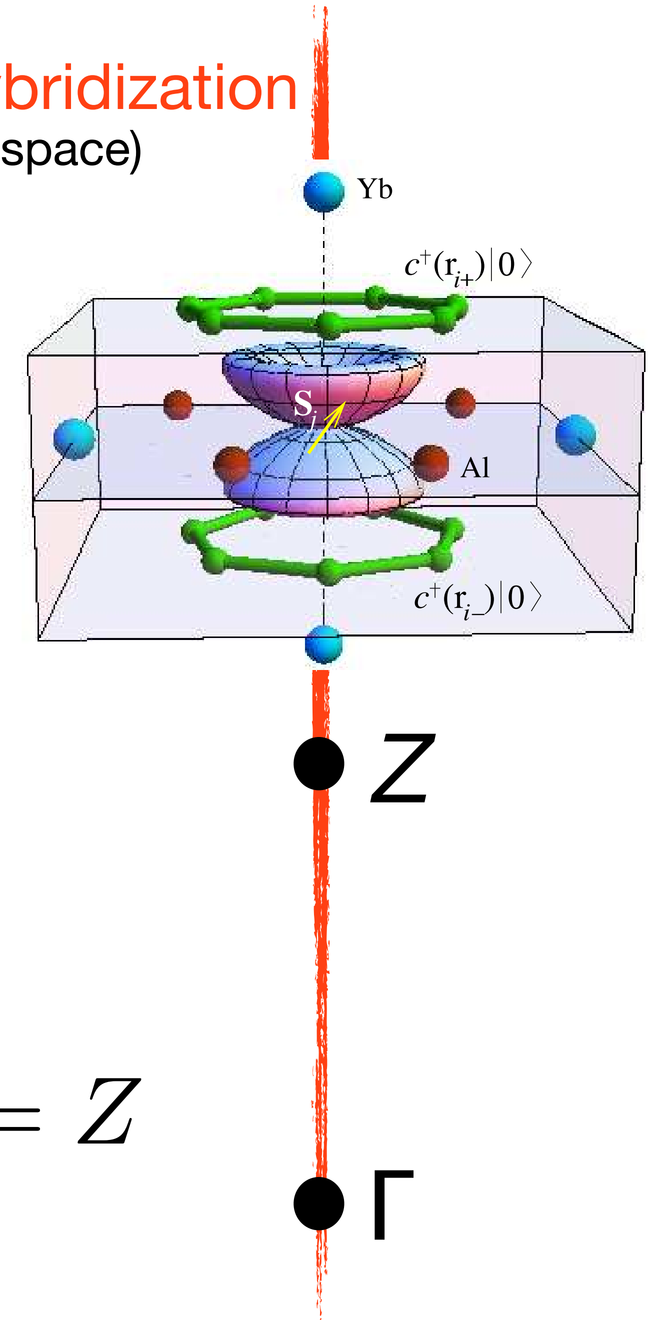

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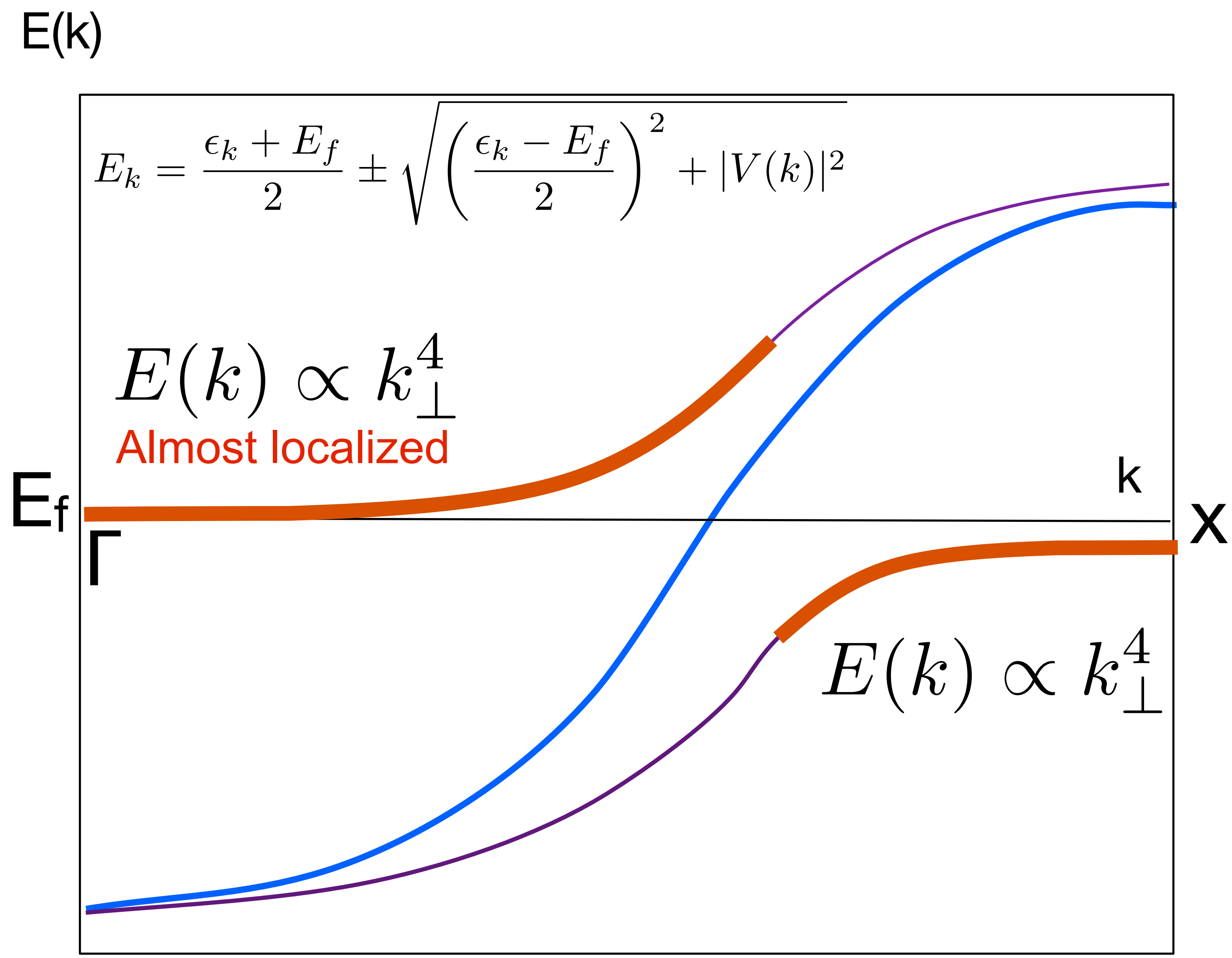
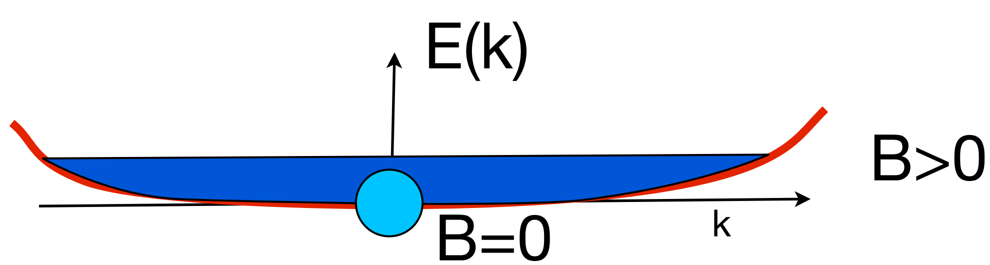
$$E_k = \frac{\epsilon_k + E_f}{2} \pm \sqrt{\left(\frac{\epsilon_k - E_f}{2}\right)^2 + |V(k)|^2}$$





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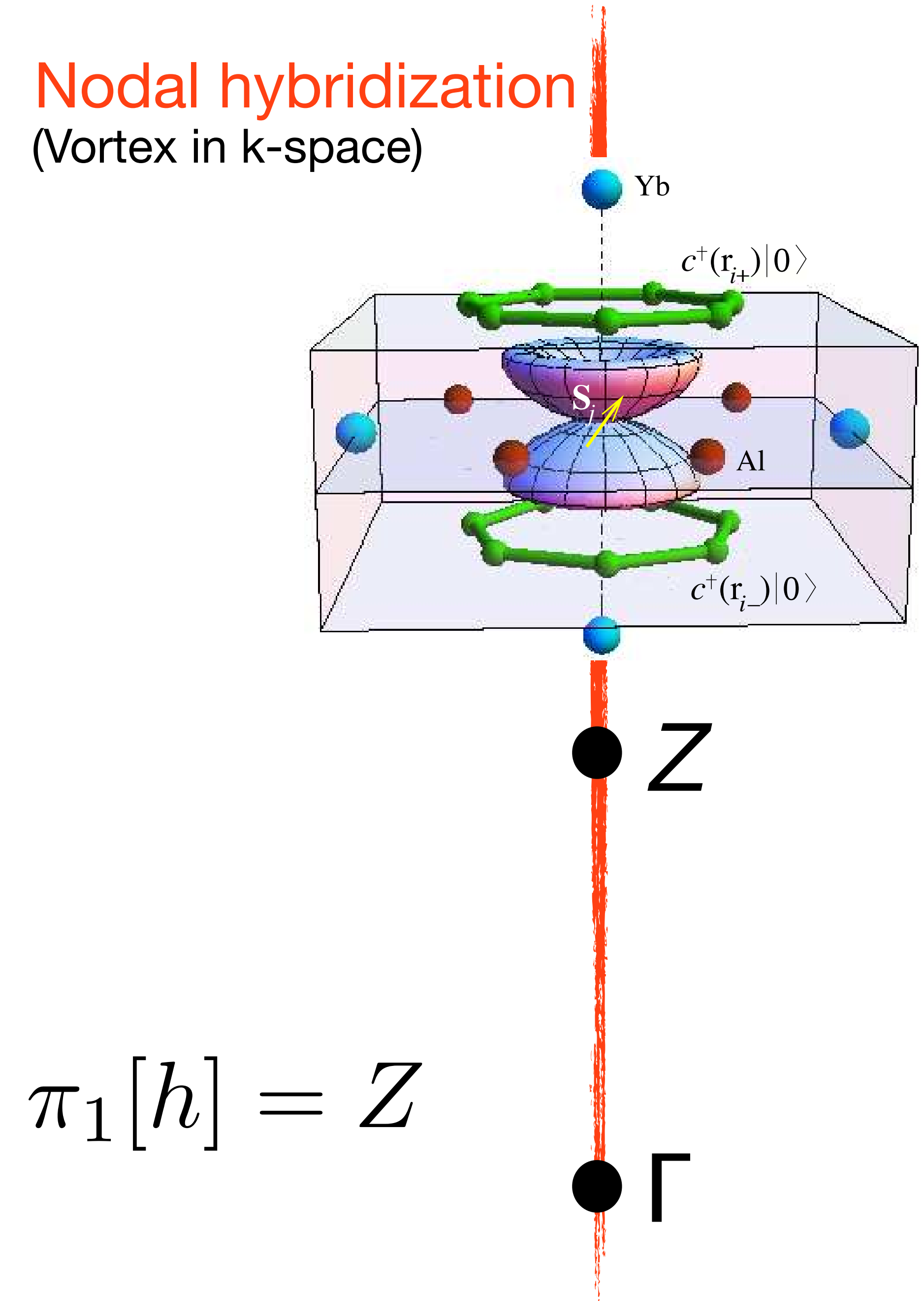

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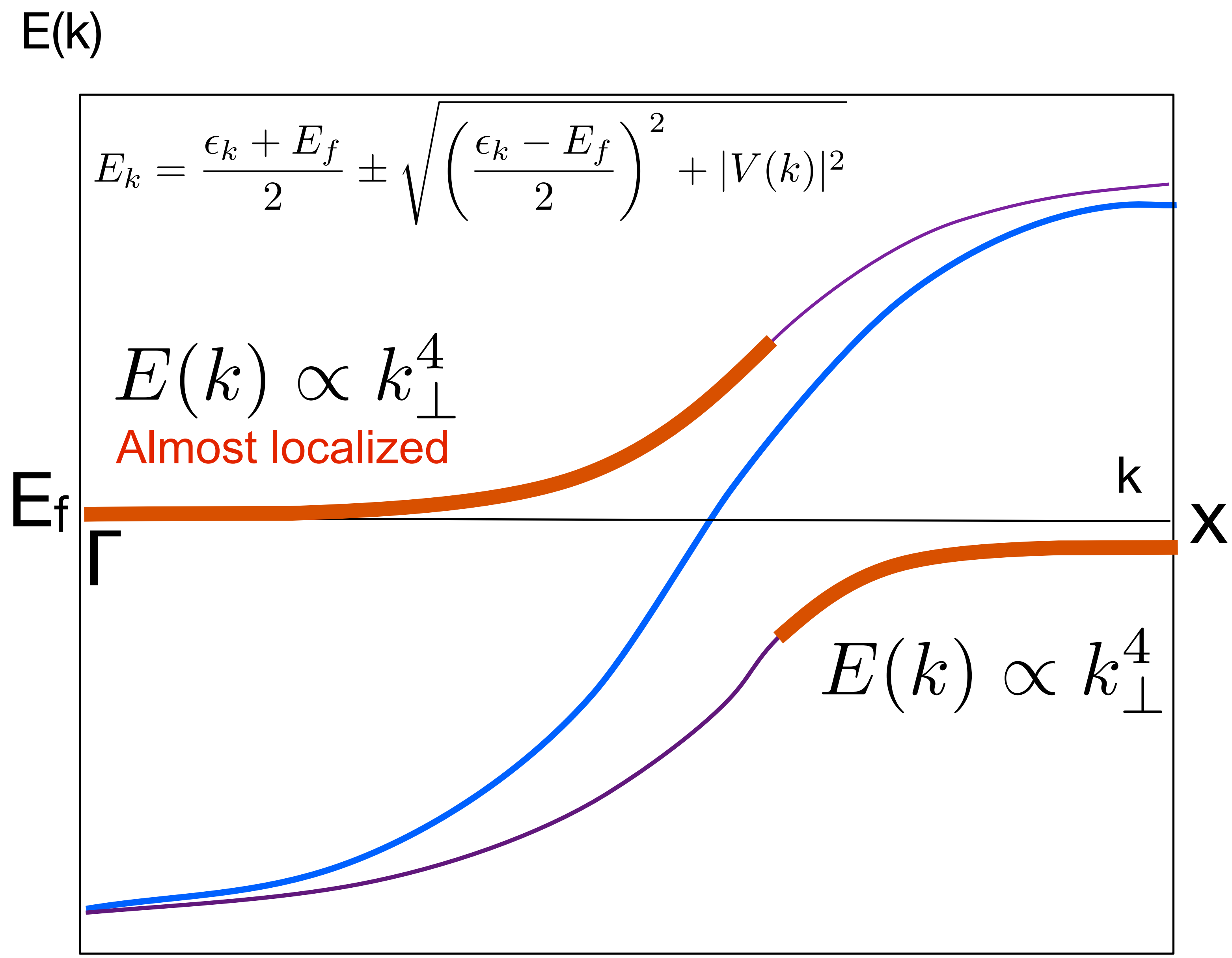

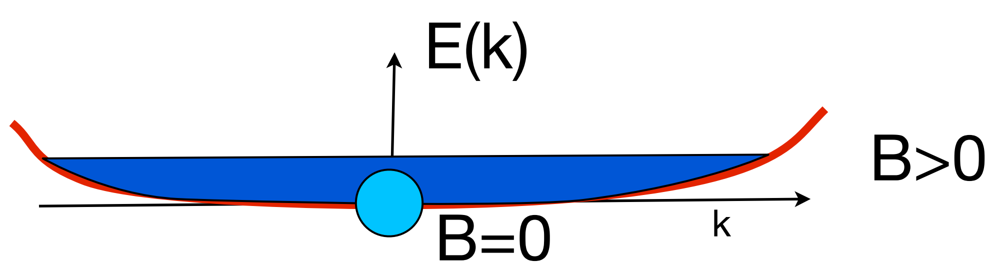

Topological Lifschitz Transition.

Nevidomskyy and Coleman (08)

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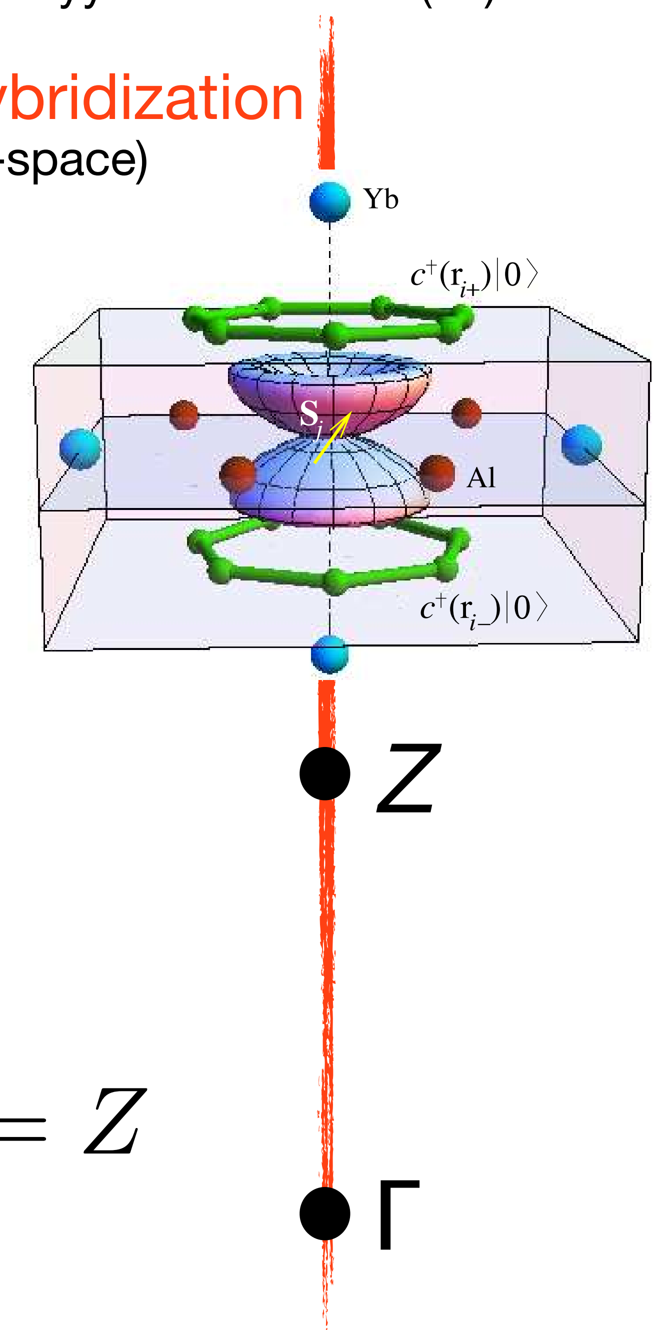

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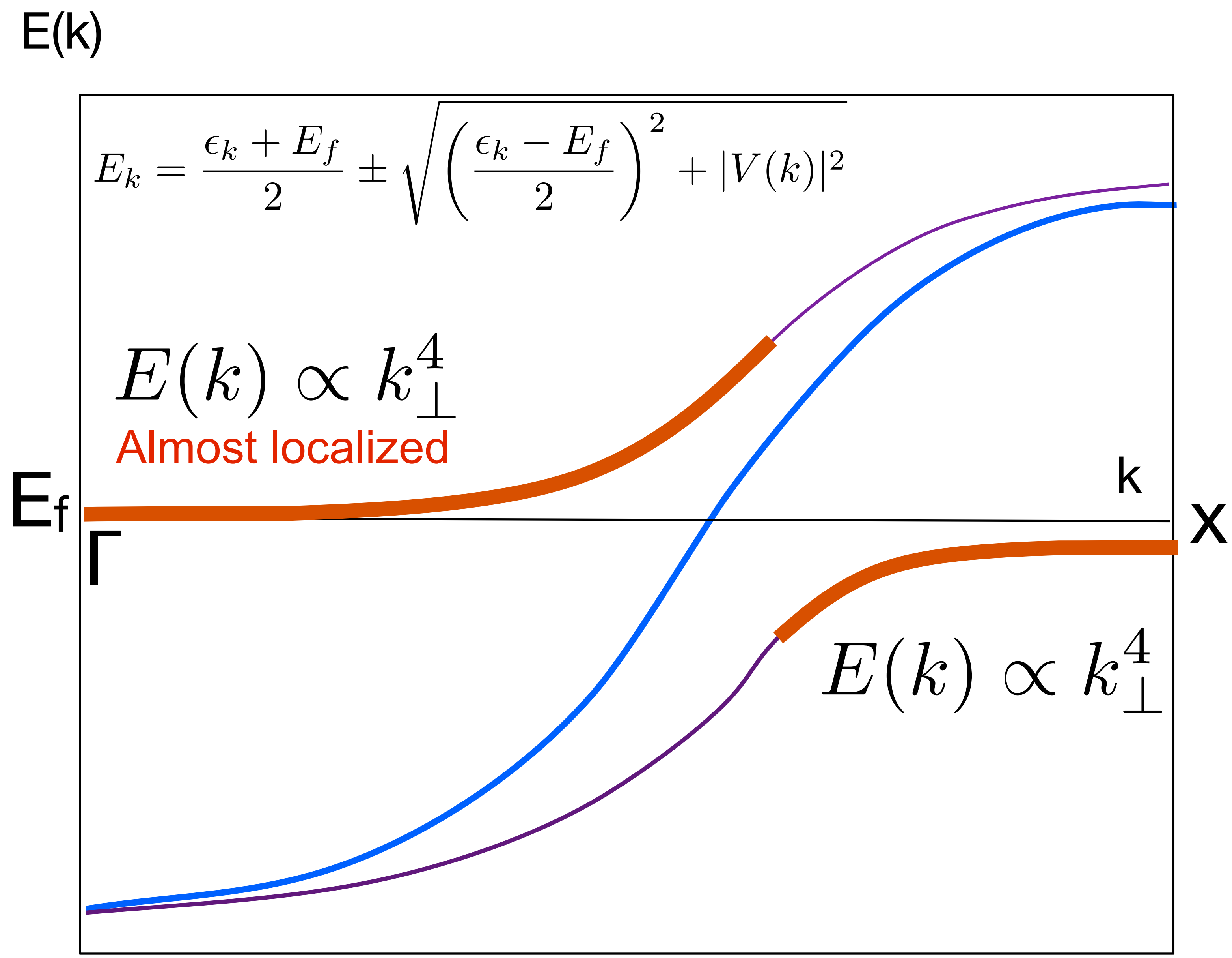

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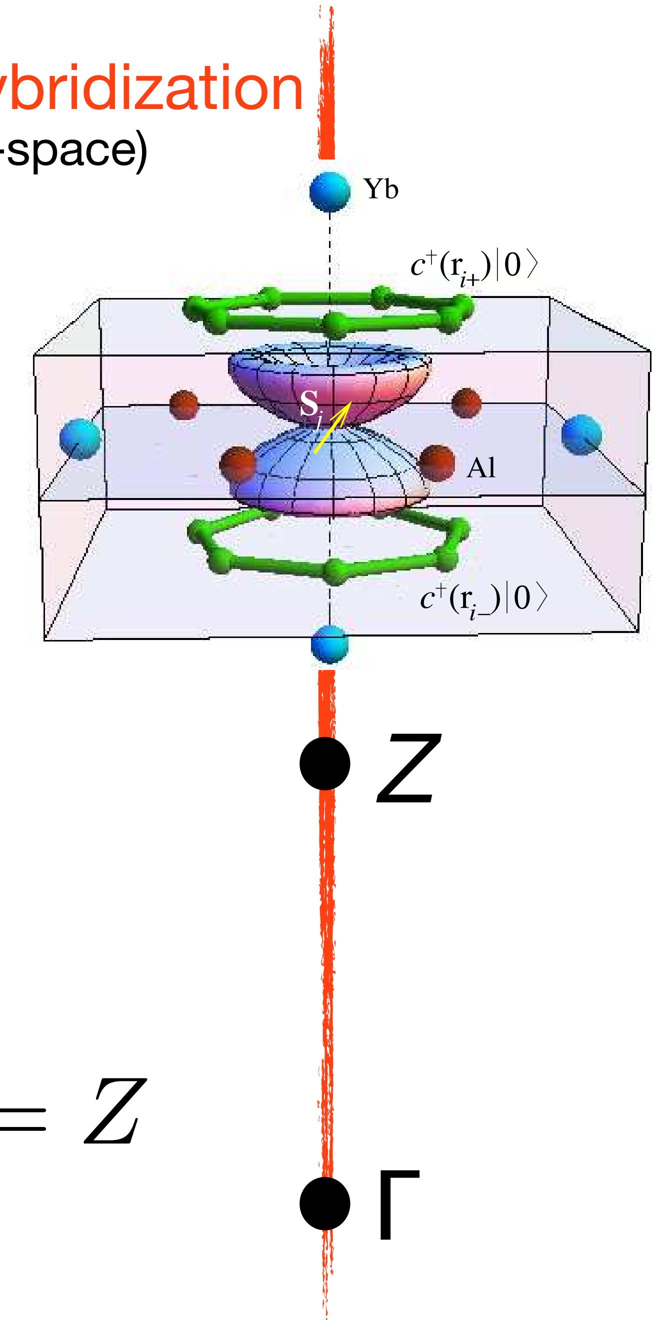

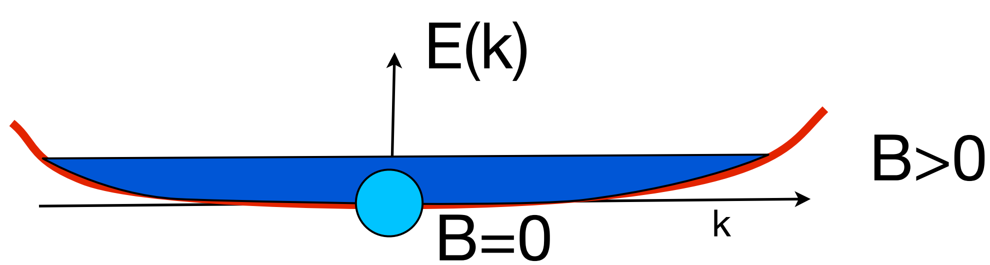

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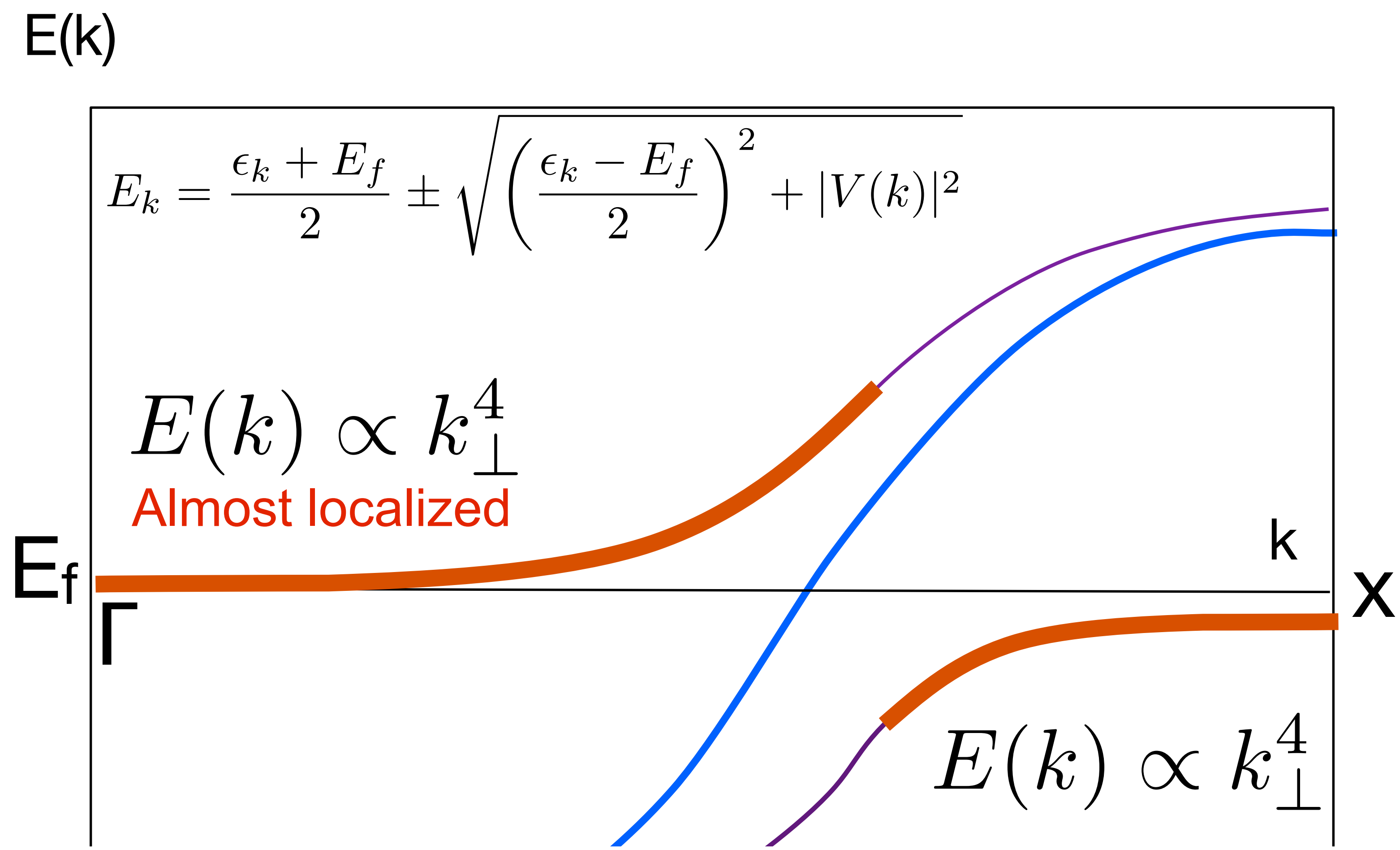
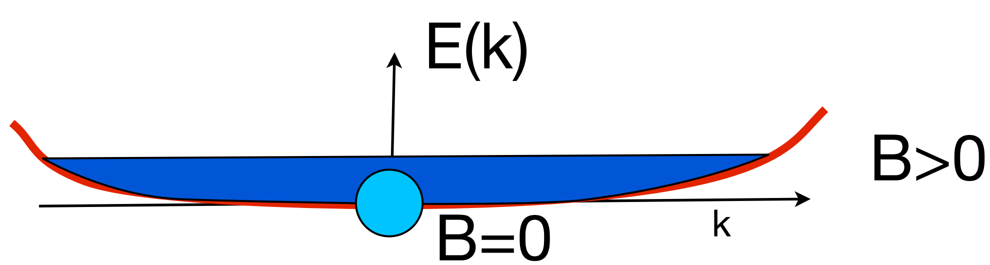


But why is the chemical potential so very precisely at zero?



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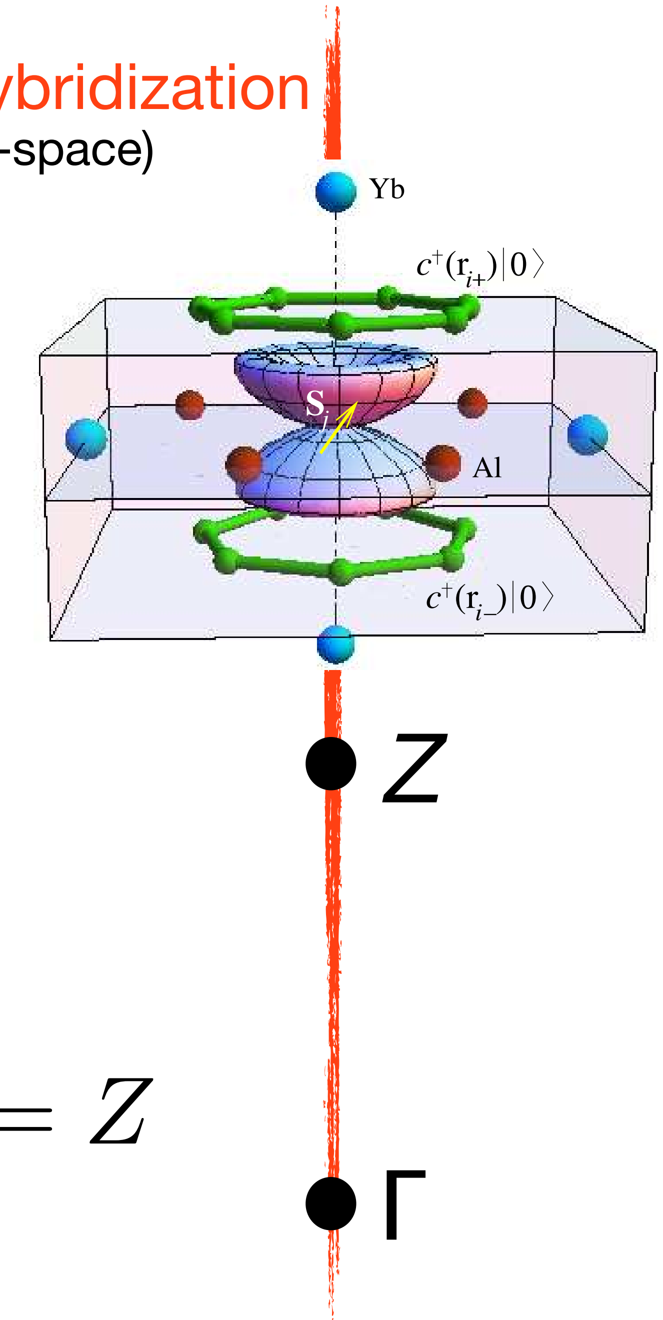

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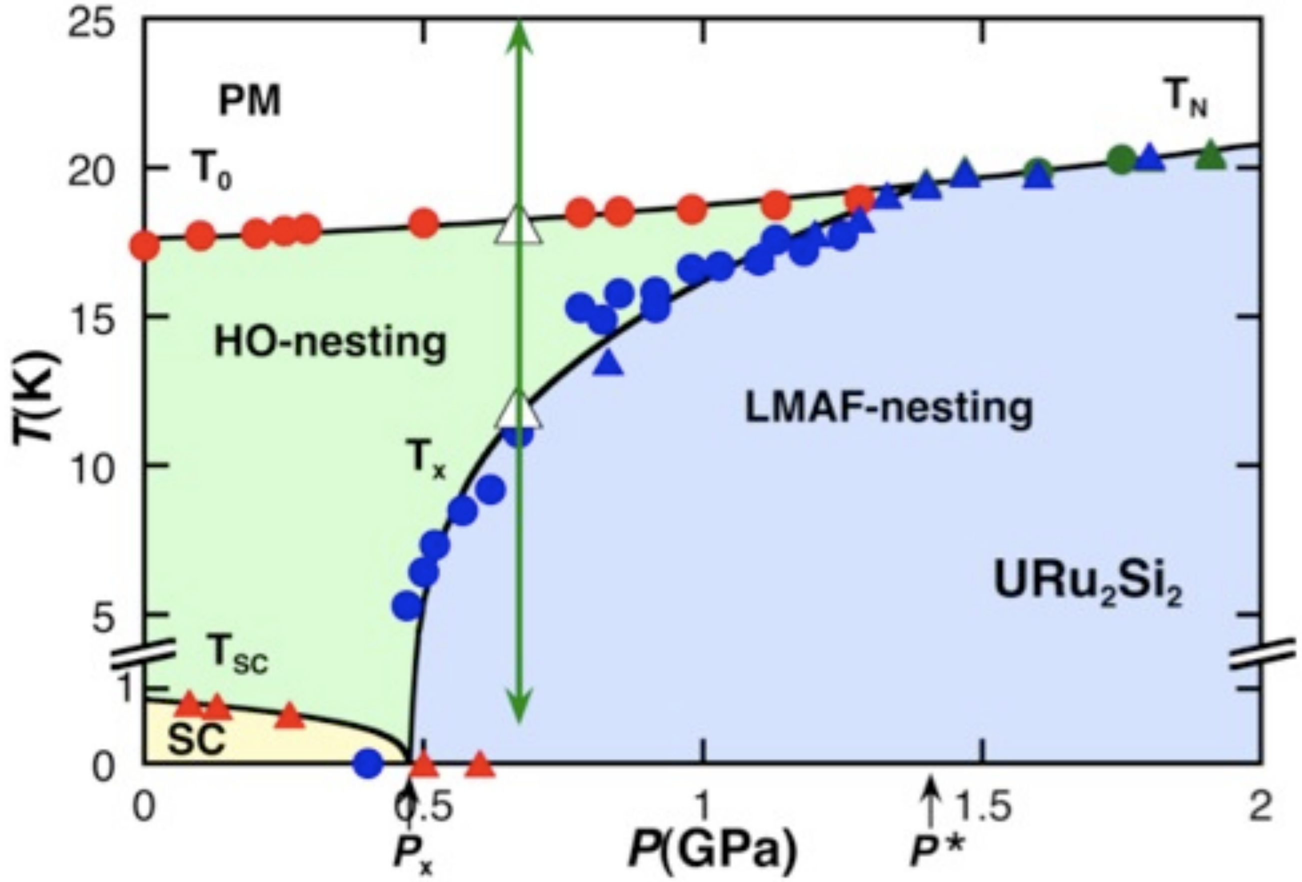
Hidden Order.

Rebecca Flint
(MIT)

Premi Chandra
(Rutgers)

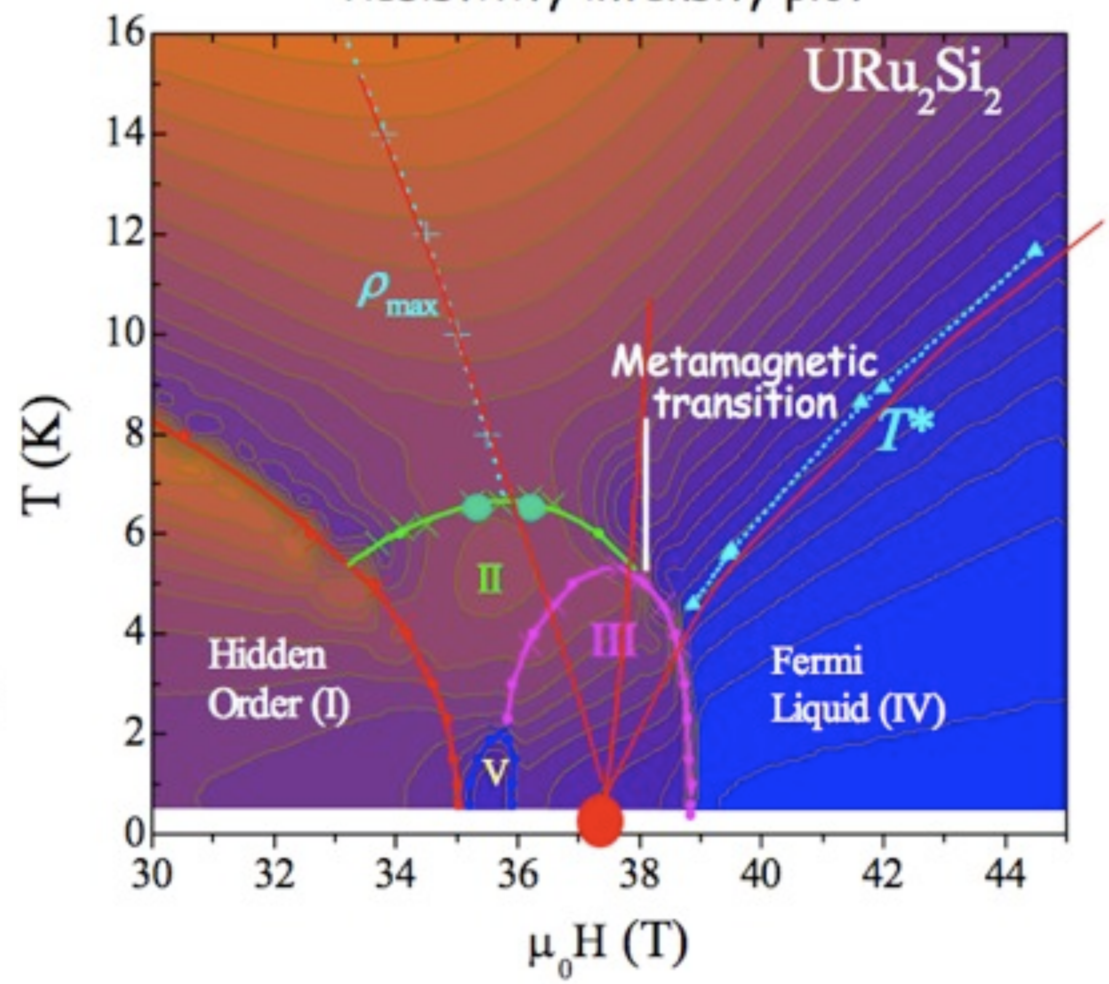
Hidden Order.

High pressures, high fields



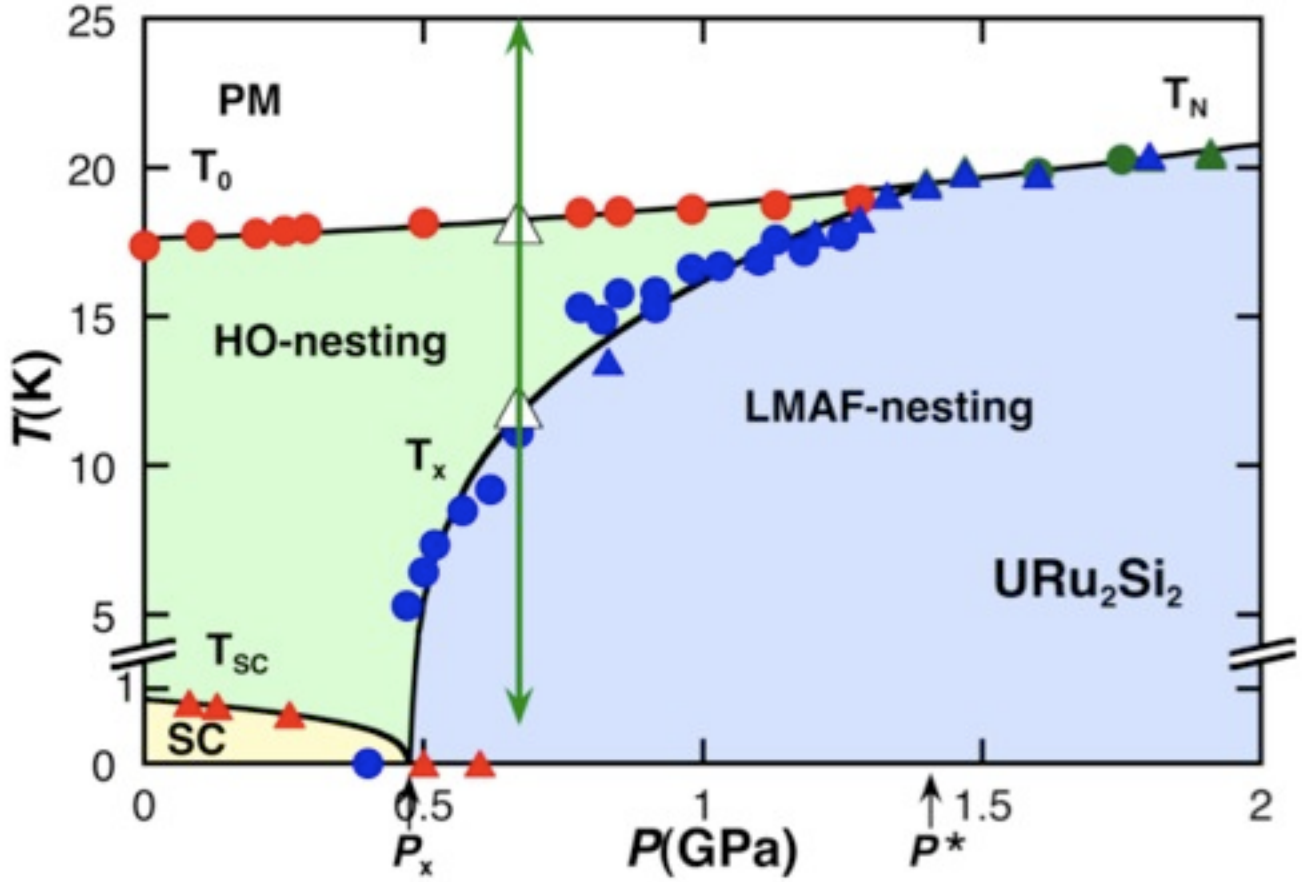
Villaume et al. (08)

Resistivity intensity plot



Kim et al (03)

High pressures, high fields



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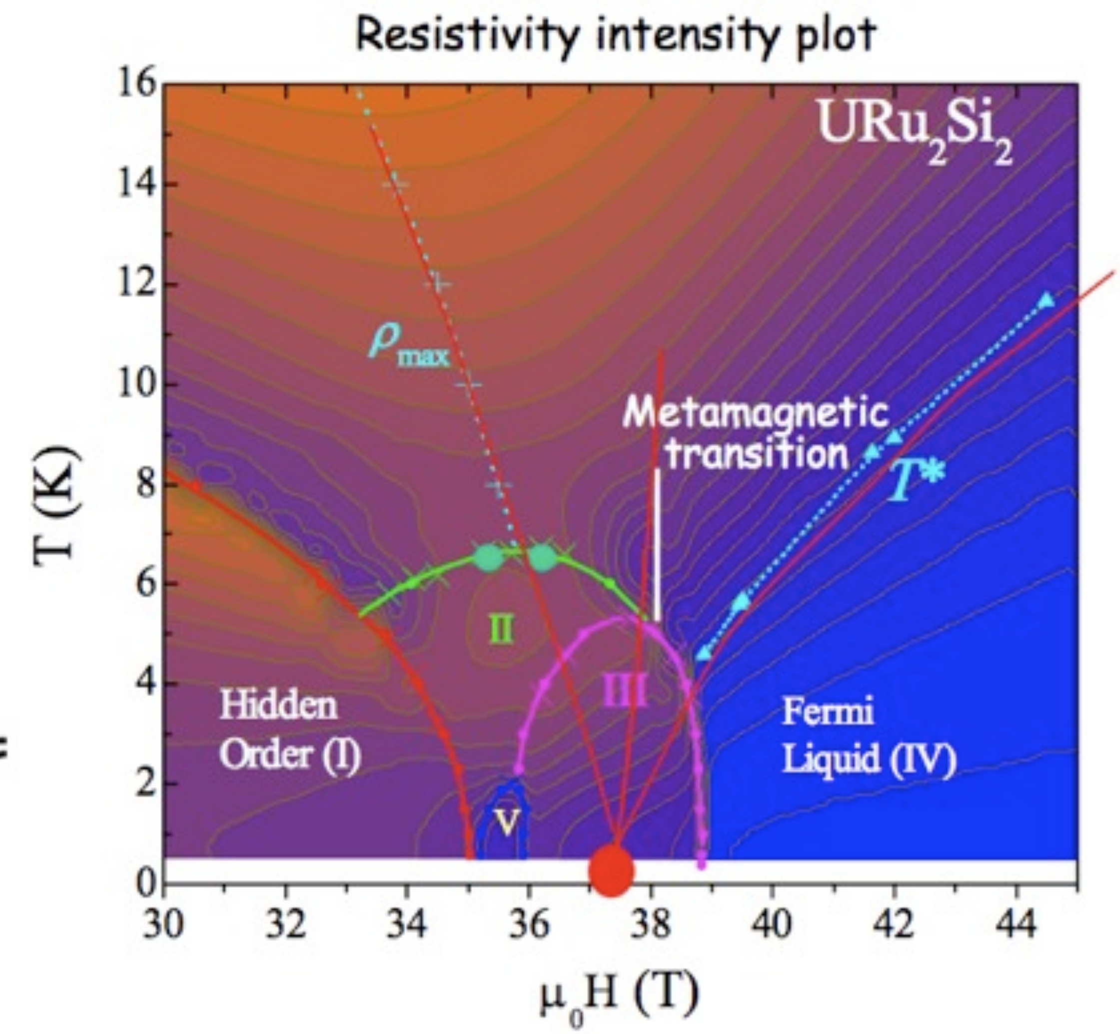


Kim et al (03)

What is the nature of the Hidden Order?

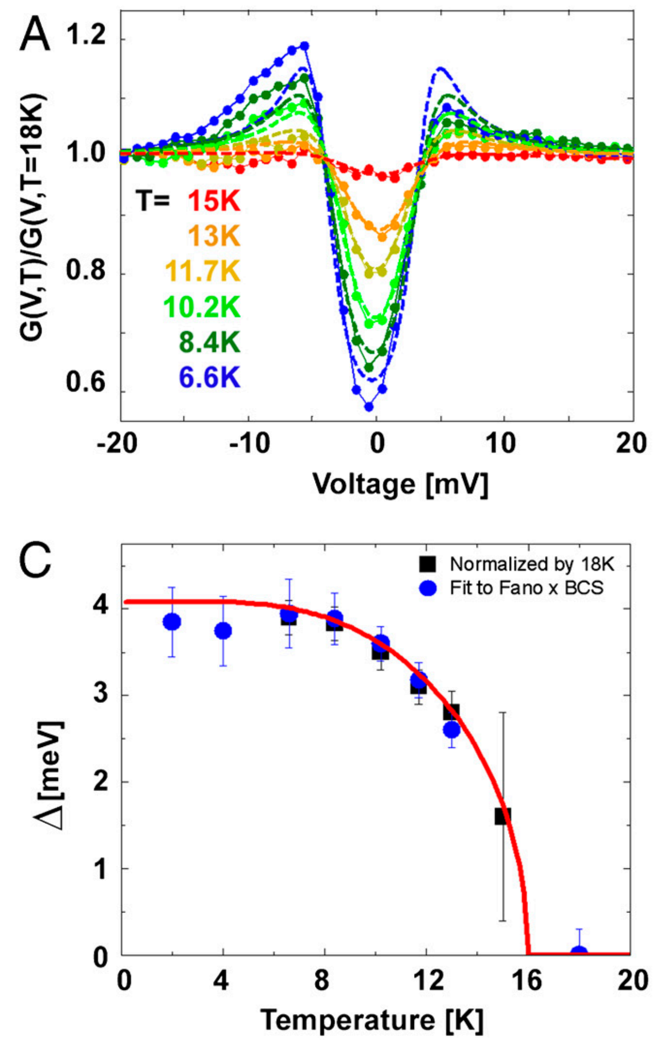
25 Years of Theoretical Proposals

Local	Barzykin & Gorkov, ’93 (three-spin correlation)
	Santini & Amoretti, ’94, Santini (’98) (Quadrupole order)
	Amitsuka & Sakihabara (Γ_5, Quadrupolar doublet, ‘94)
	Kasuya, ’97 (U dimerization)
	Kiss and Fazekas ’04, (octupolar order)
	Haule and Kotliar ’09 (hexa-decapolar)
Landau Theory	Shah et al. (’00) “Hidden Order”,
Itinerant	Ramirez et al, ’92 (quadrupolar SDW)
	Ikeda and Ohashi ’98 (d-density wave)
	Okuno and Miyake ’98 (composite)
	Tripathi, Chandra, PC and Mydosh, ’02 (orbital afm)
	Dori and Maki, ’03 (unconventional SDW)
	Mineev and Zhitomirsky, ’04 (SDW)
	Varma and Zhu, ’05 (spin-nematic)
	Ezgar et al ’06 (Dynamic symmetry breaking)
	Pepin et al ’10 (Spin liquid/Kondo Lattice)
	Dubi and Balatsky, ’10 (Hybridization density wave)
	Fujimoto, 2011 (spin-nematic)

Spectroscopy:
H-gap in STM/Optics

* cf Session P1, Weds 8am, room A1

Aynajian* et al, PNAS (2010)



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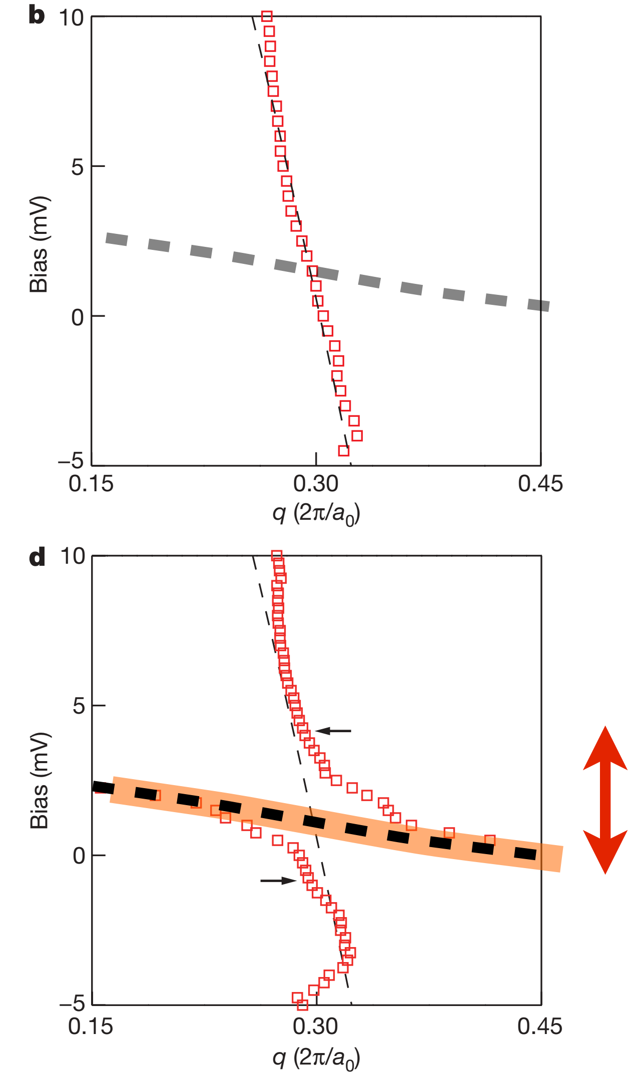

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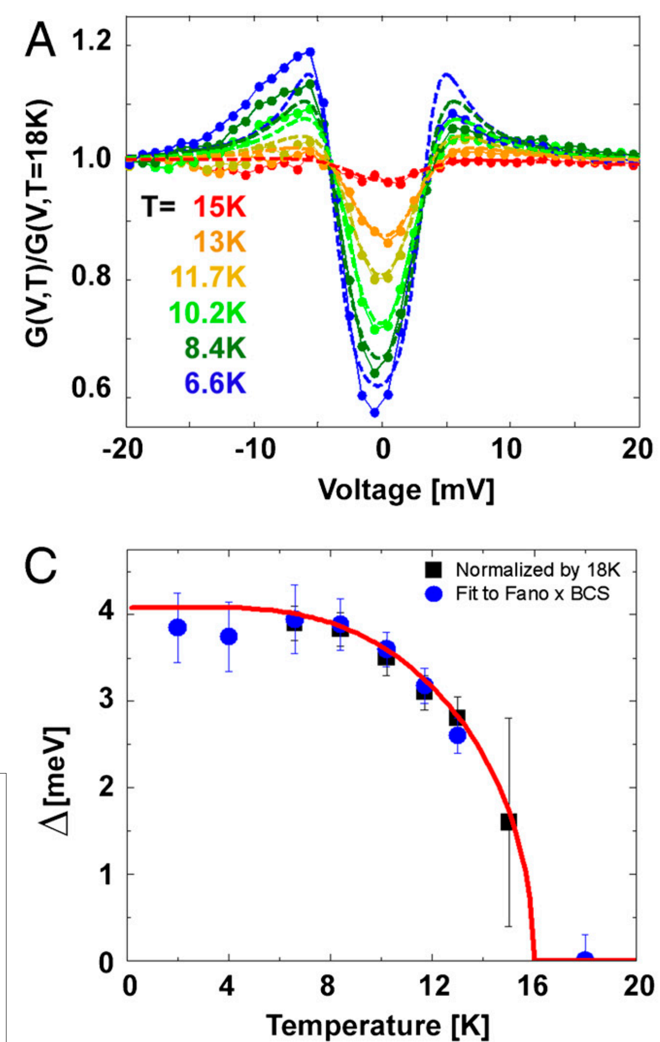

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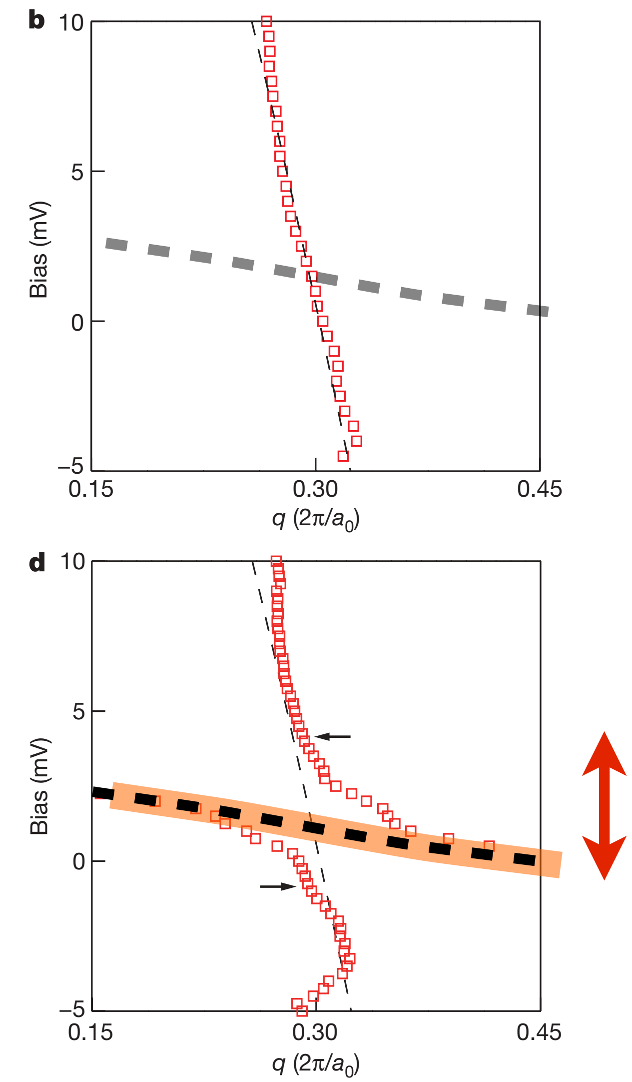

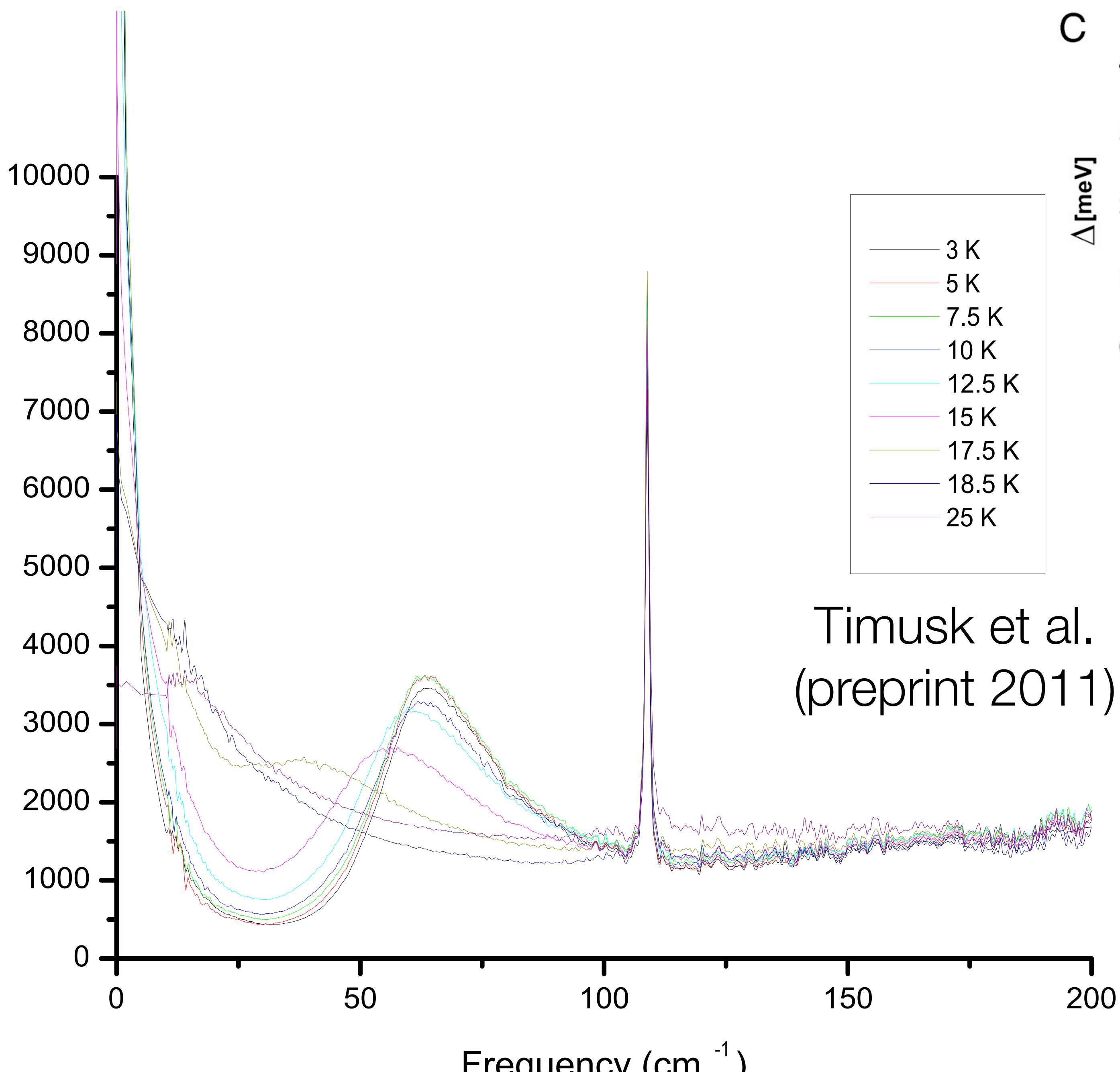

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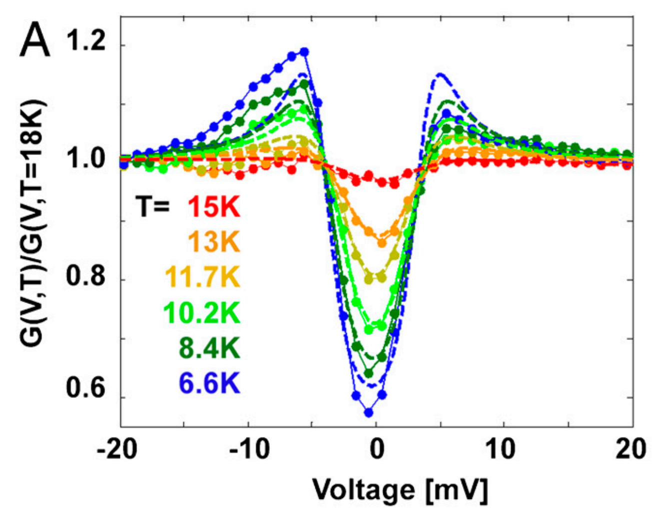

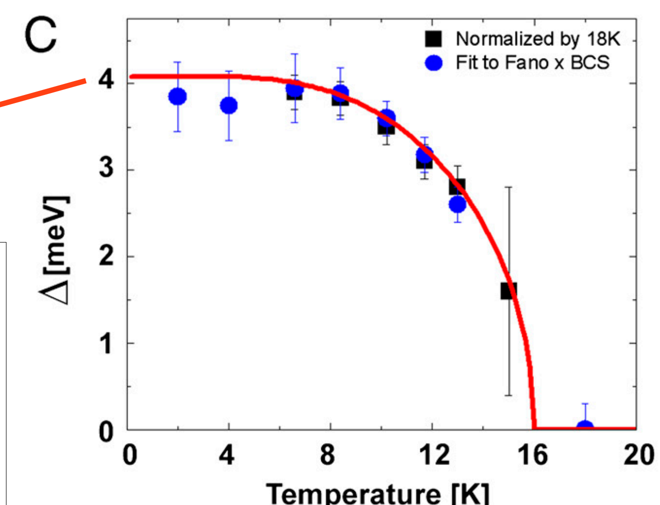

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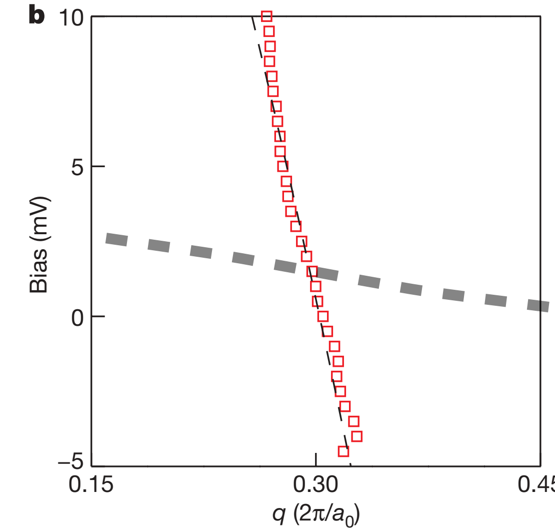

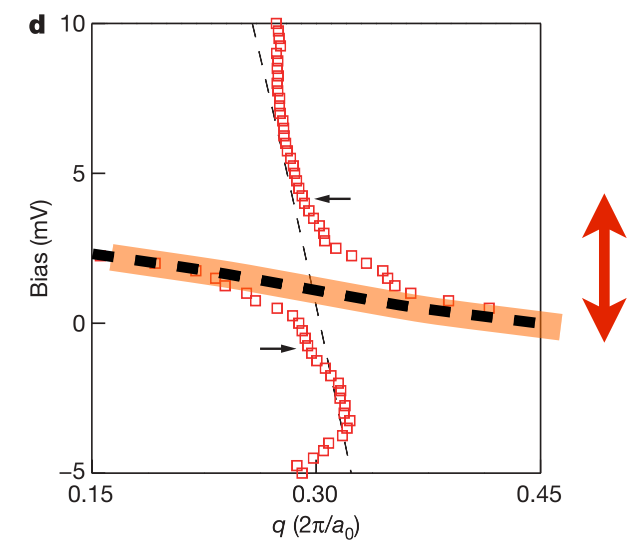

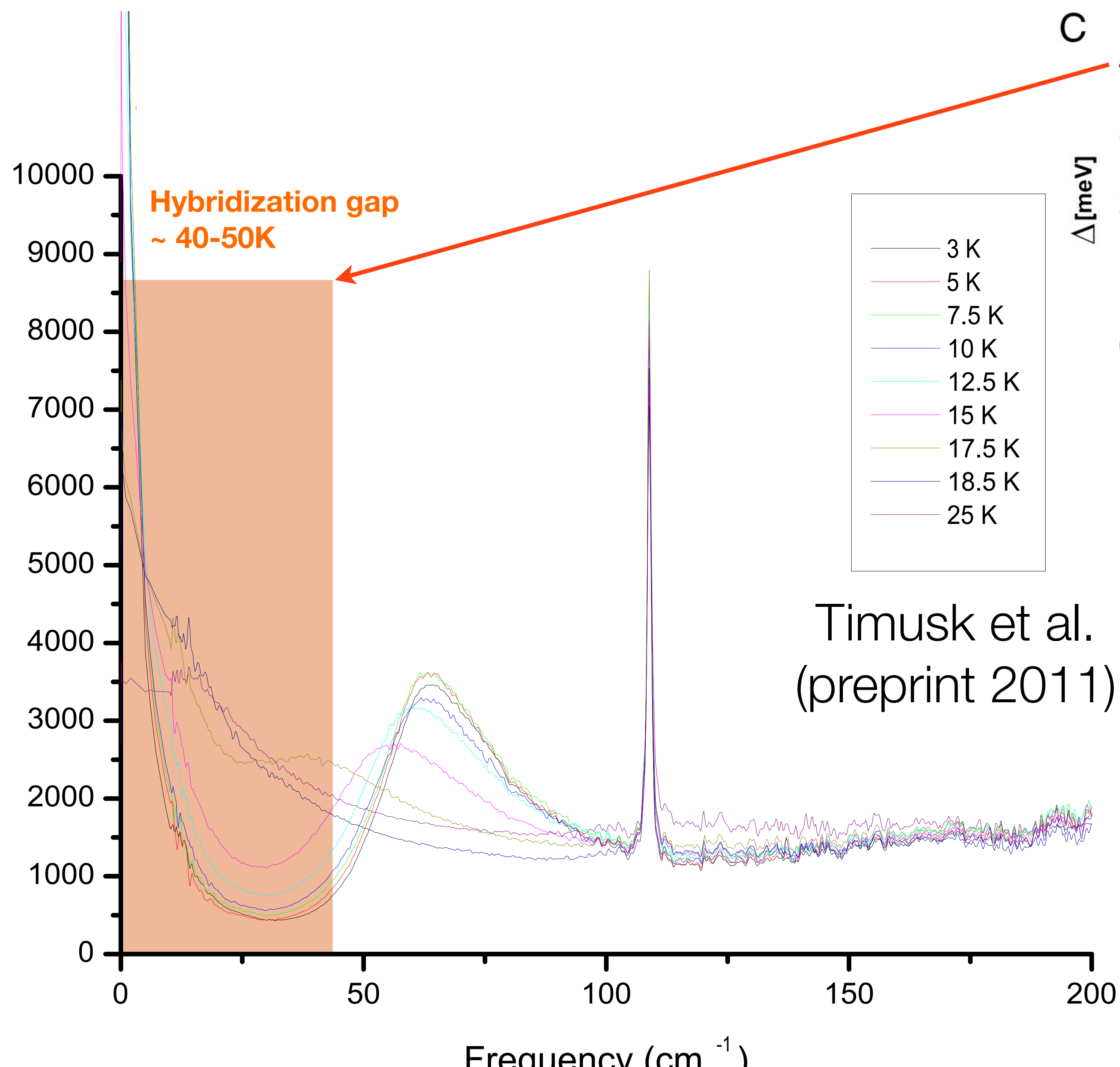

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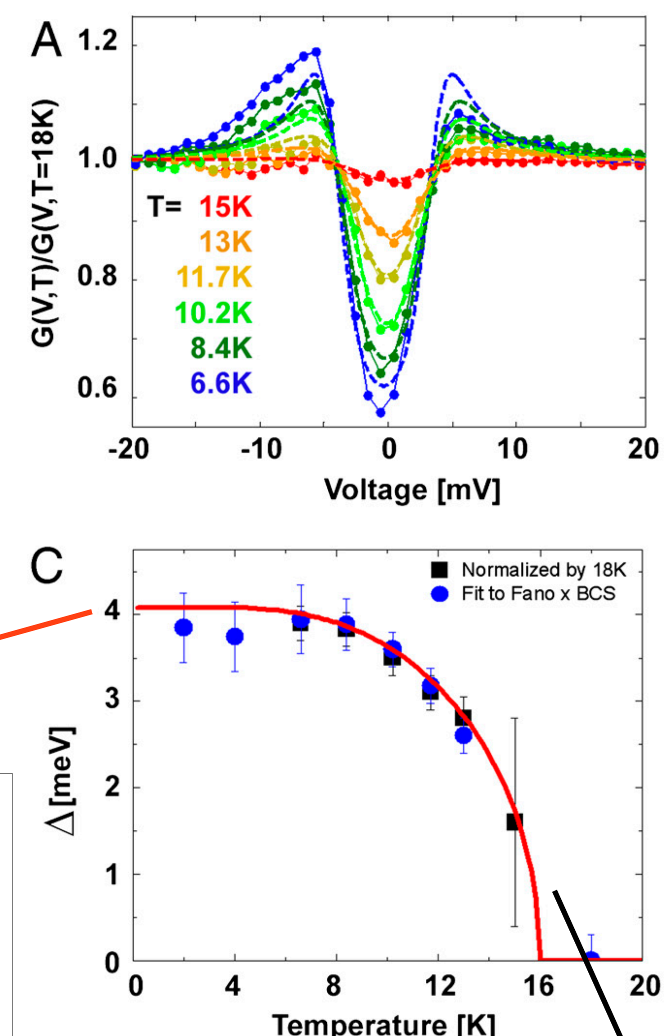

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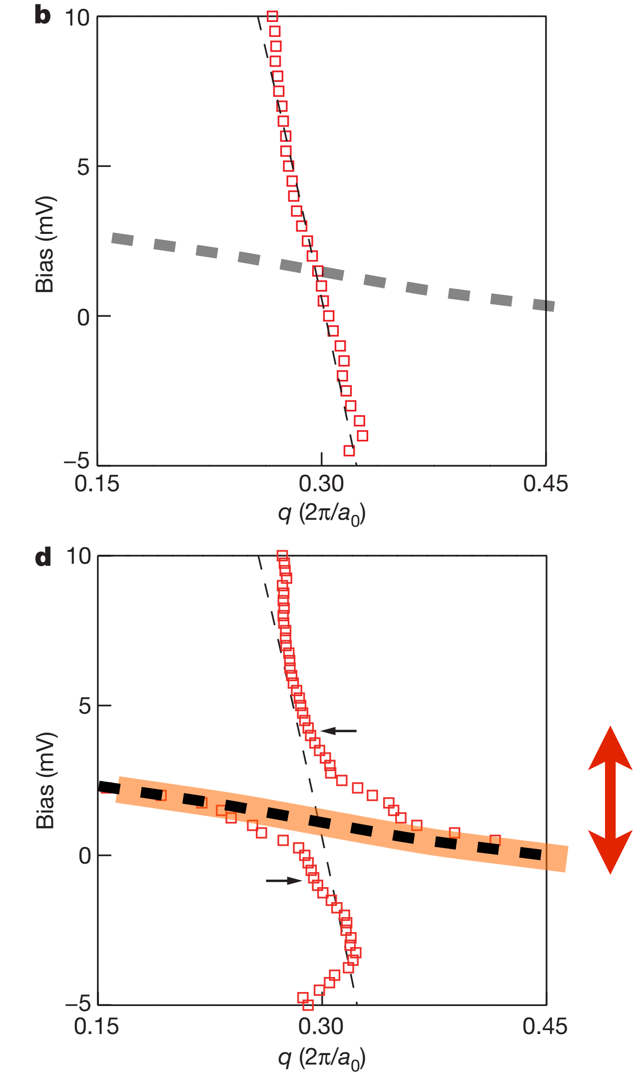

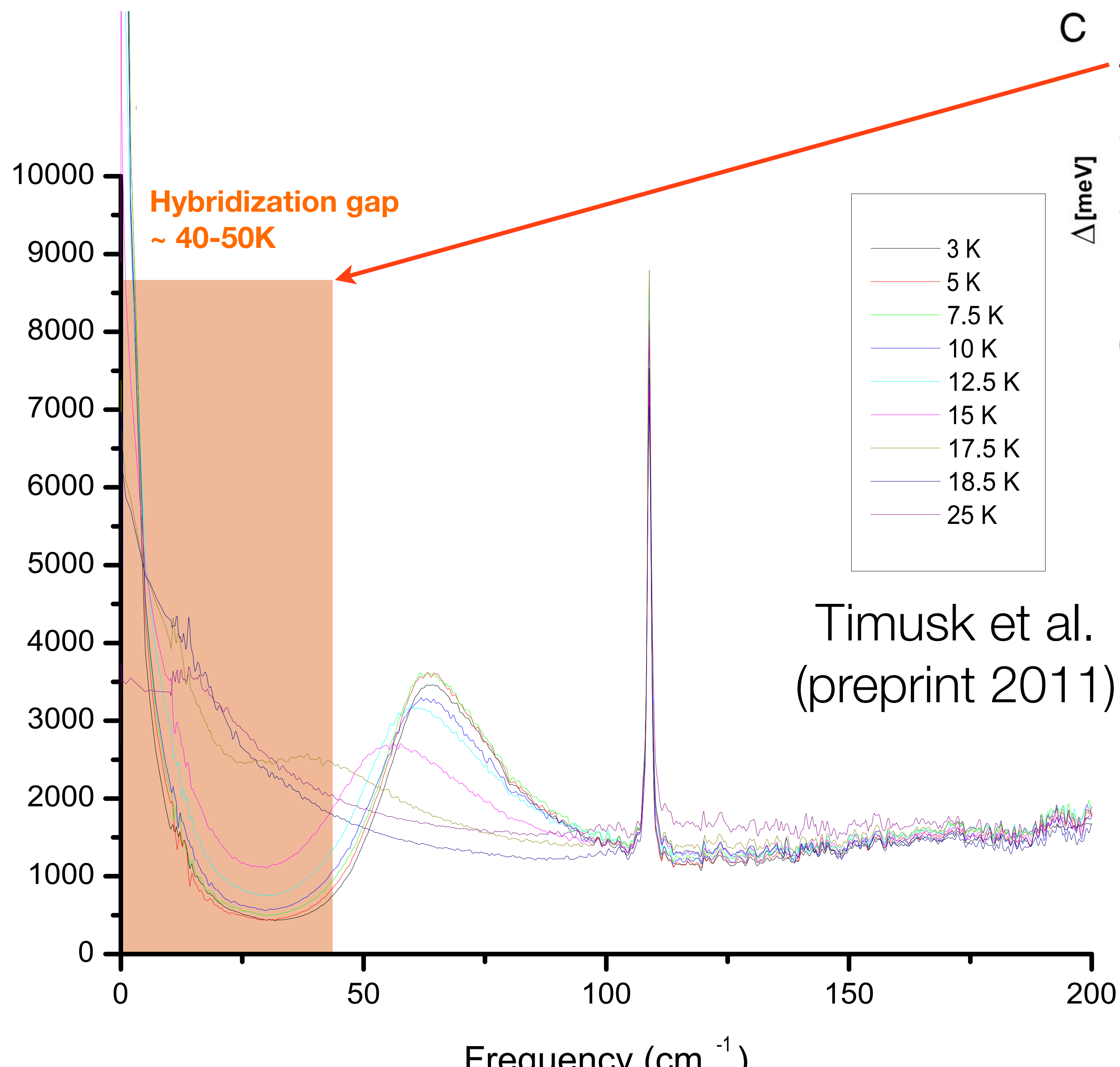

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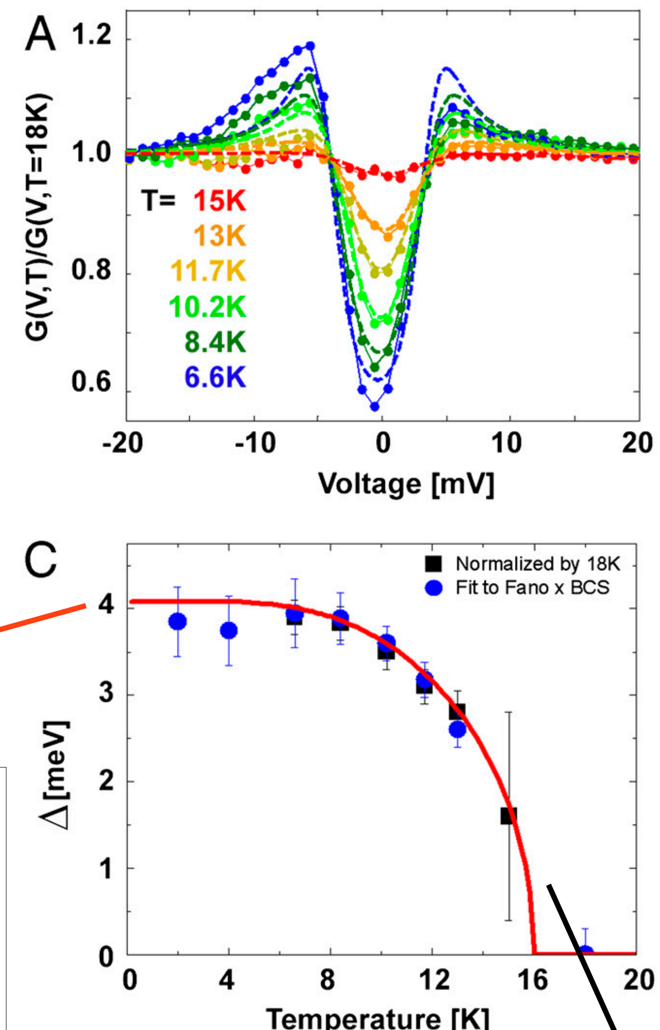

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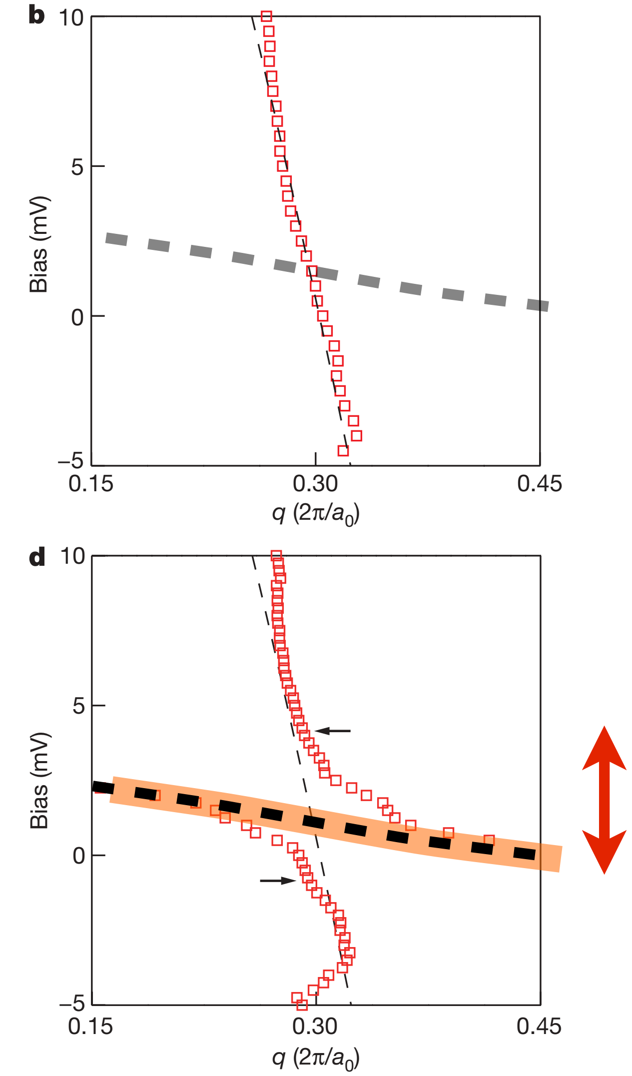

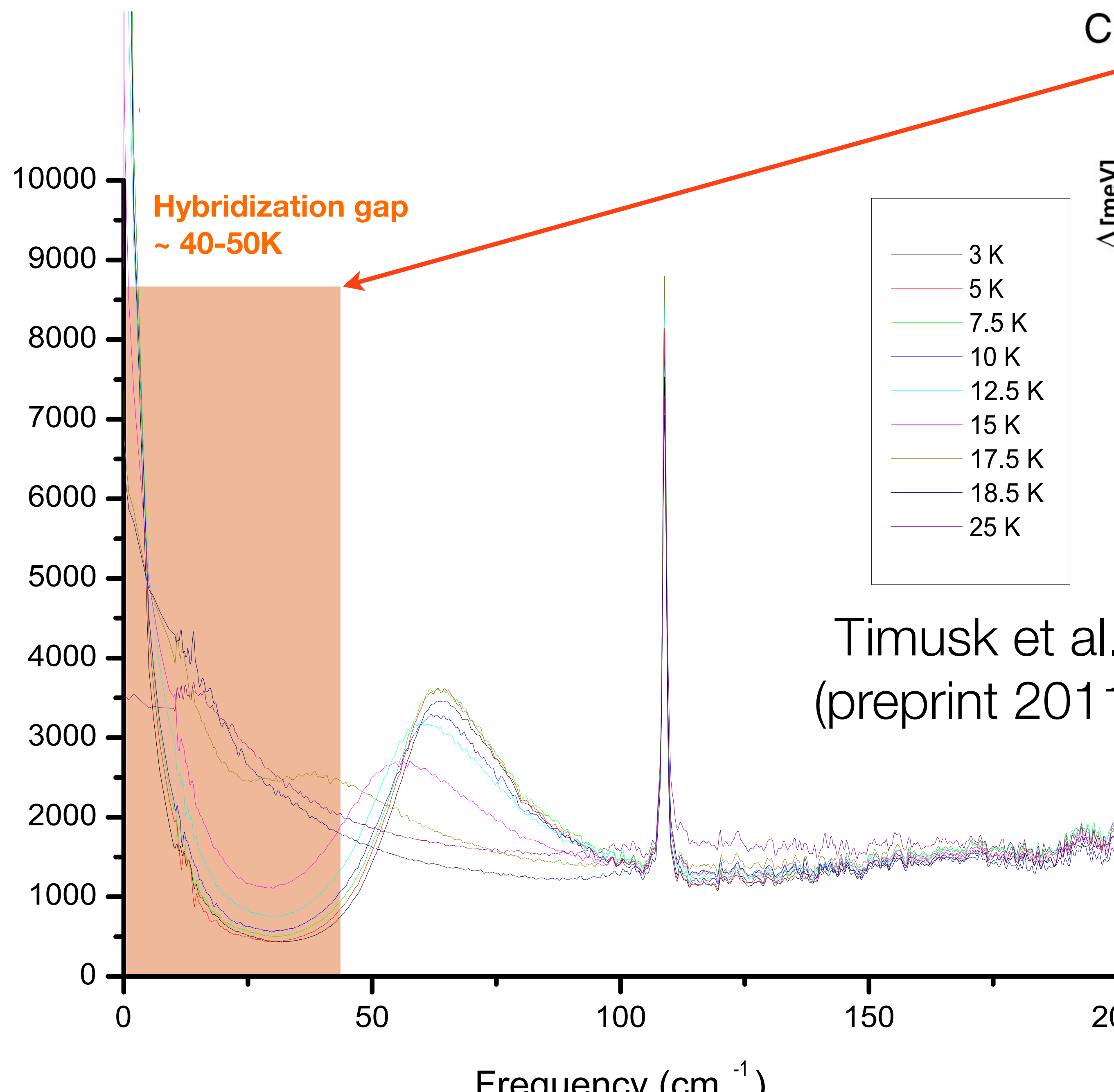

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Hybridization *is* the order parameter.

Morr et al (10), Dubi and Balatsky(10)

Quantum Oscillations: Giant Ising Anisotropy

$$M \propto \cos\left[2\pi \frac{\text{Zeeman}}{\text{cyclotron}}\right]$$

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Spin Zero condition

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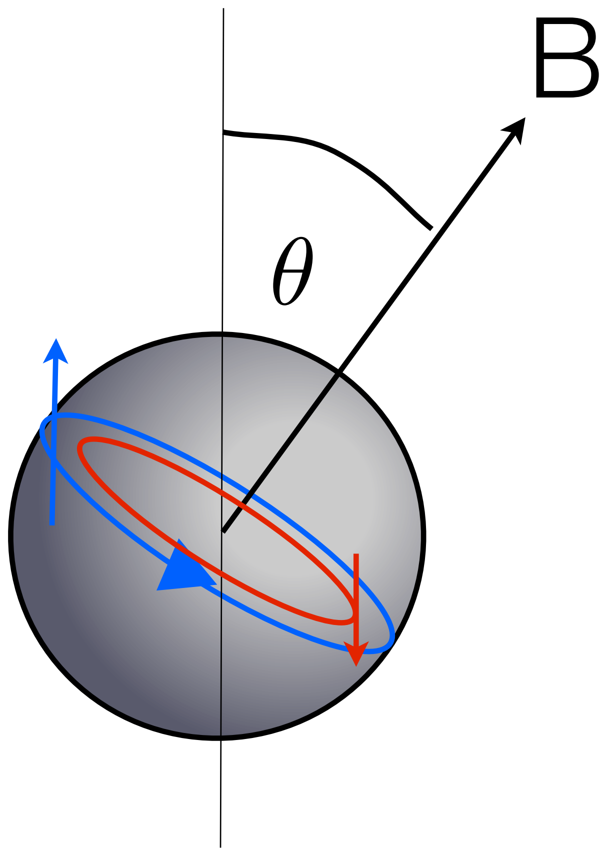

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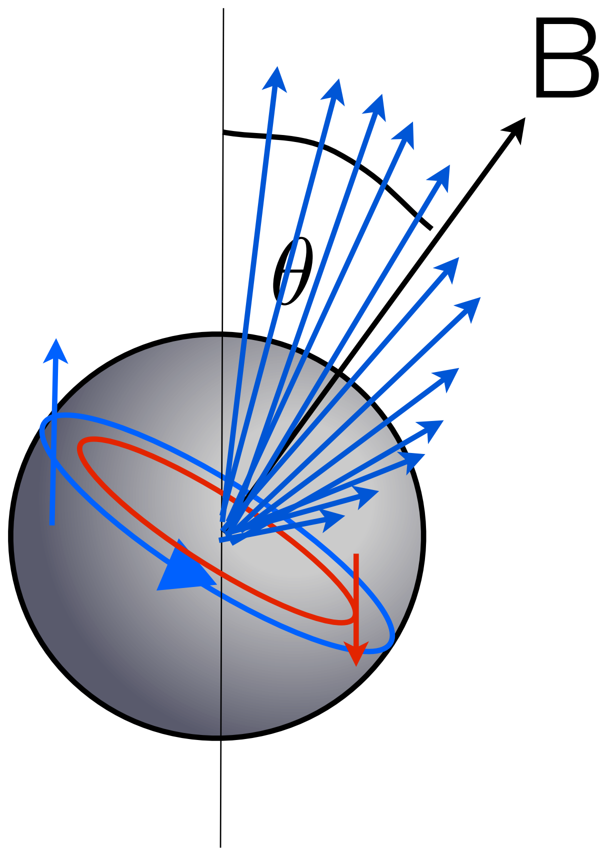

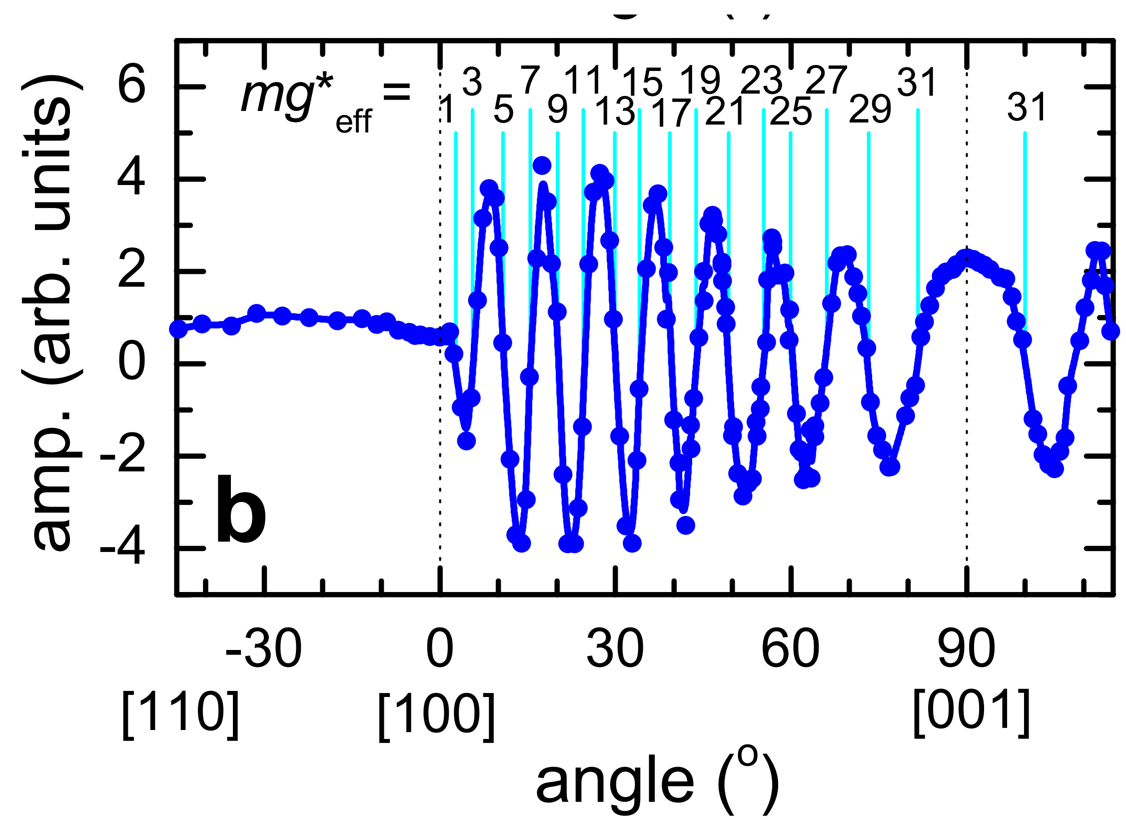

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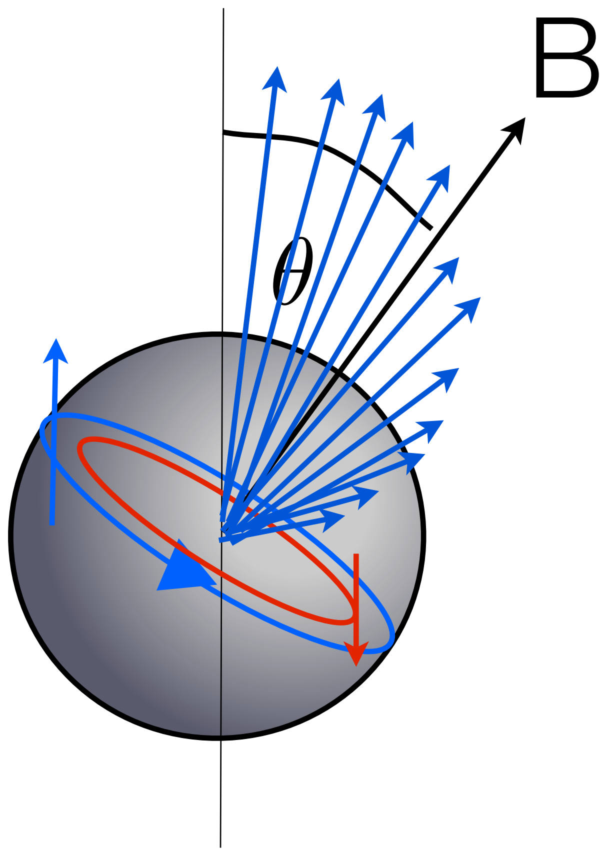

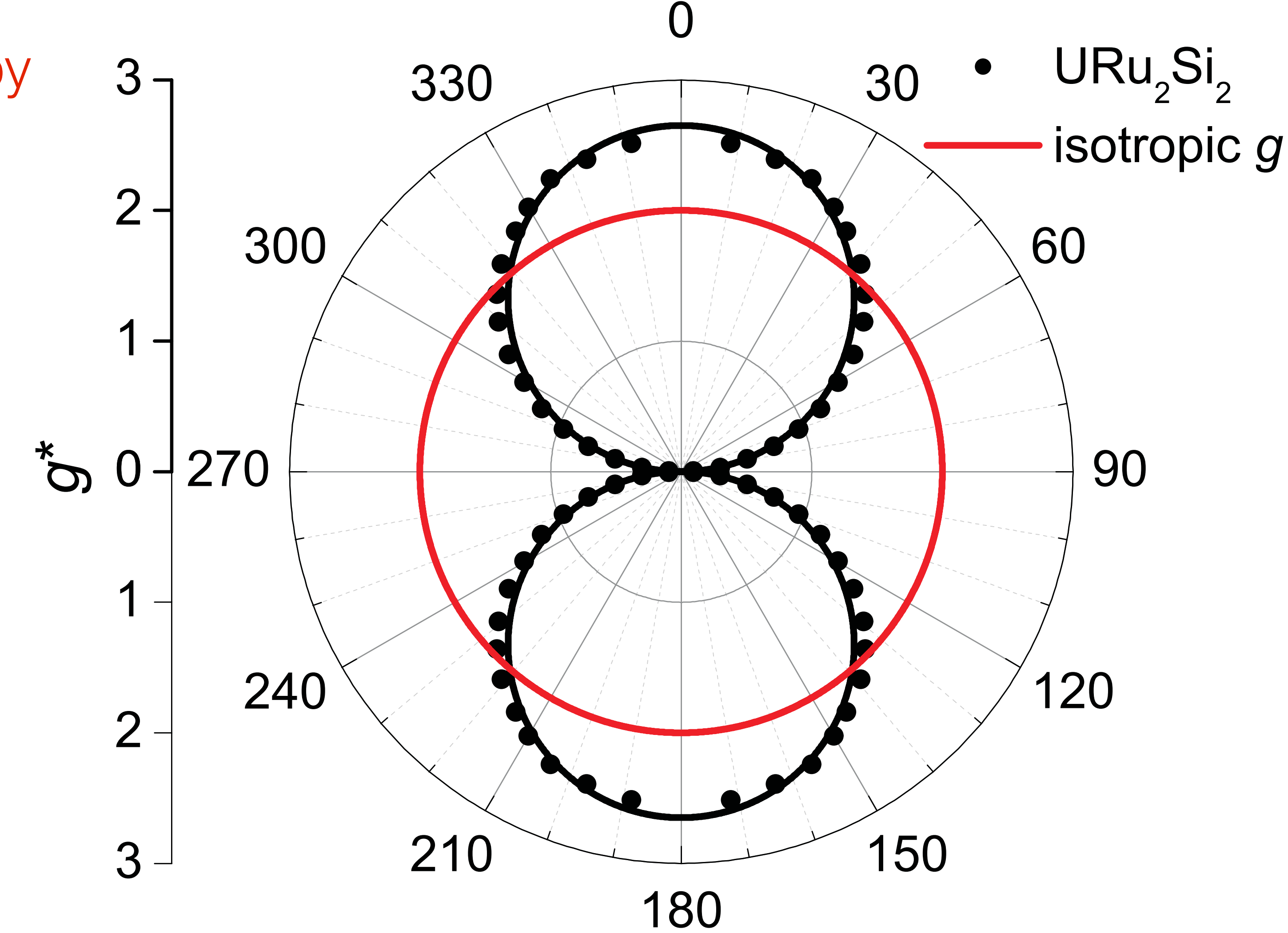

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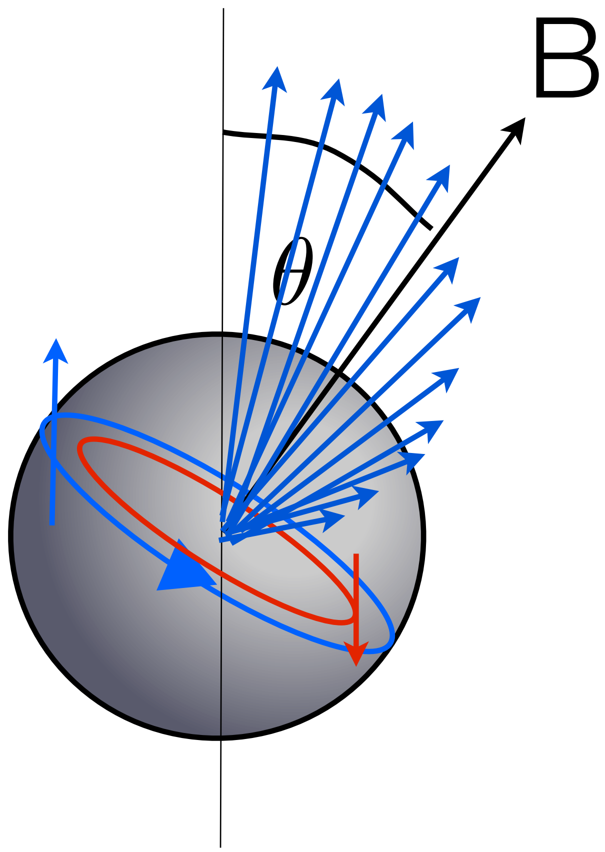

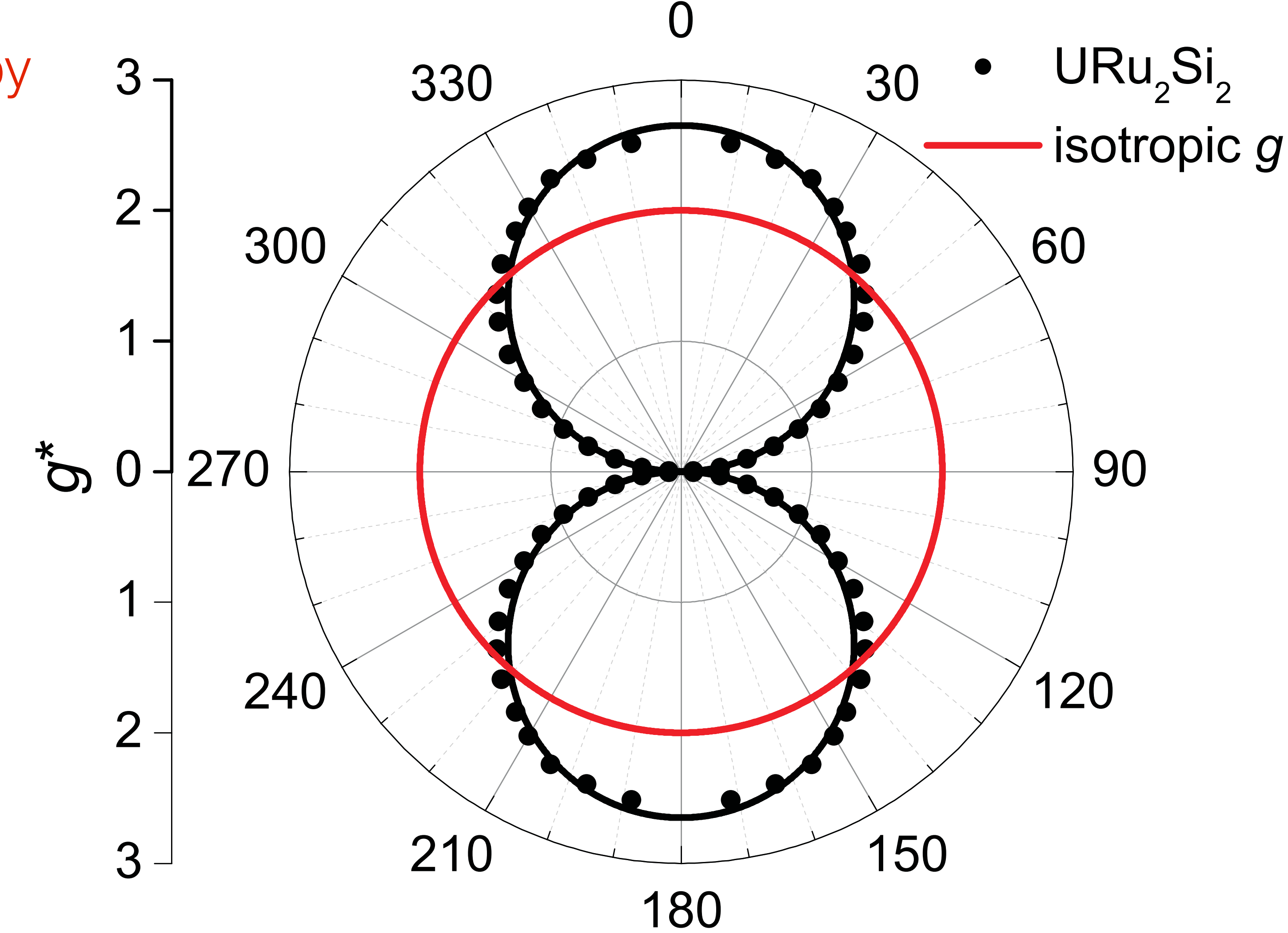

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Ising *quasiparticle* with giant Ising anisotropy > 25.
Pauli susceptibility anisotropy > 500

Symmetry Implications of giant Ising anisotropy

Kramers index K: quantum no of ***double*** time reversal $\theta \times \theta = \theta^2$.

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$$V|\mathbf{k}\sigma\rangle\langle m| + \text{H.c}$$

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θ^2 is equivalent to a 2π rotation: $$\Theta^2|\psi\rangle = K|\psi\rangle = |\psi^{2\pi}\rangle$$

Half-integer spins change sign, integer spins do not.

$$K = (-1)^{2J}$$

Giant Ising anisotropy indicates hybridization between electrons |**kσ** 〉 and **integer** spin f^2 non-Kramers doublet |m〉. (nb: Kramers doublets do not have Ising symmetry in a tetragonal environment without fine-tuning.) Under a double time reversal

$$V|\mathbf{k}\sigma\rangle\langle m| \rightarrow V^{2\pi}|\mathbf{k}\sigma^{2\pi}\rangle\langle m^{2\pi}| = -V^{2\pi}|\mathbf{k}\sigma\rangle\langle m|$$

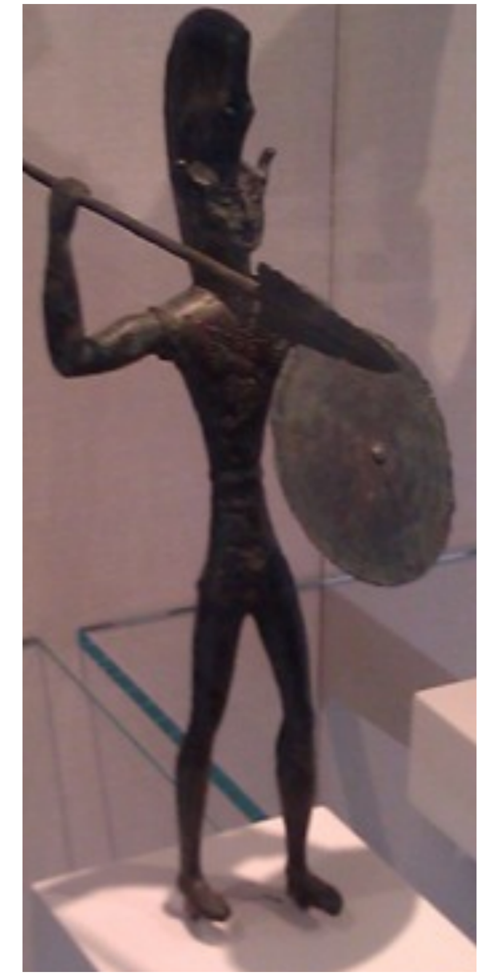
Since the microscopic Hamiltonian must be Kramers-invariant,

$$V = -V^{2\pi}$$

i.e. the hybridization transforms as a half-integer spin, and therefore has spinorial character. Unlike magnetism, it breaks both single and double time reversal symmetry and is thus a new kind of order parameter.

“Hastatic order”

hasta: spear (latin)



Γ_5 : Fundamentally Ising.

$$b = \begin{pmatrix} b_\uparrow \\ b_\downarrow \end{pmatrix} \longrightarrow \begin{pmatrix} \langle b_\uparrow \rangle \\ \langle b_\downarrow \rangle \end{pmatrix}$$

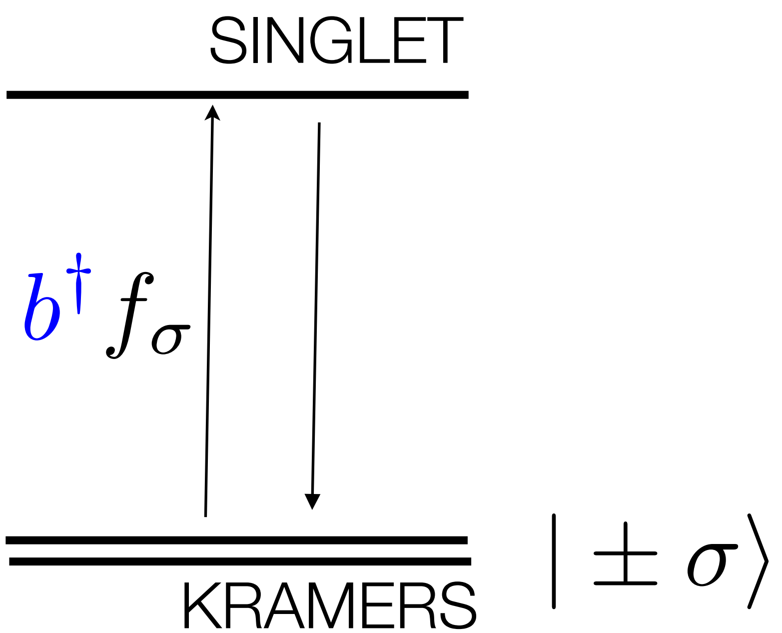
$$b = \Psi_H \begin{pmatrix} e^{-i(\mathbf{Q}\cdot\mathbf{x}+\phi)/2} \\ e^{i(\mathbf{Q}\cdot\mathbf{x}+\phi)/2} \end{pmatrix}$$

Hidden order: $M_f = 0$, $M_{cond} \sim TK/D$

“Hastatic” order.

"Hastatic" order.

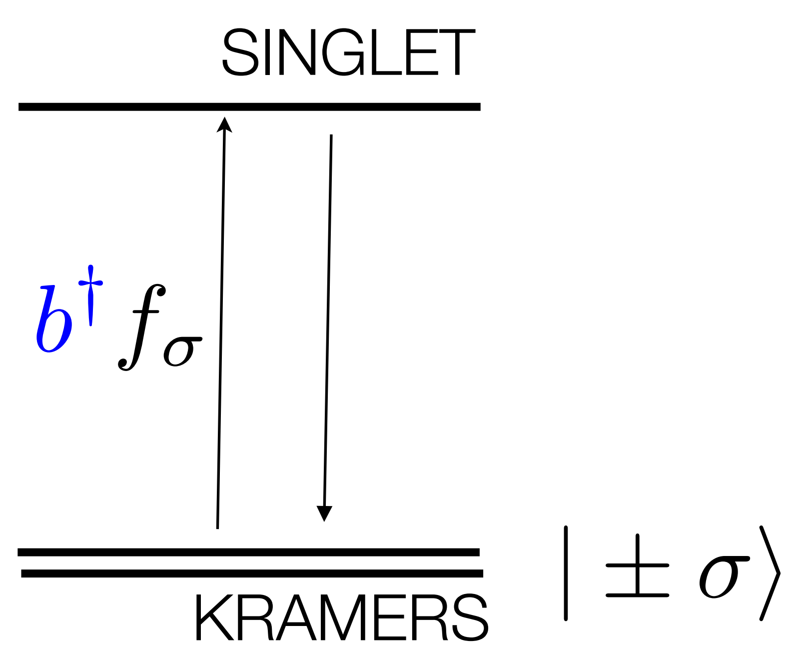
In heavy fermions a hybridization derives from virtual excitations between a Kramers doublet and an excited singlet. A uniform hybridization breaks no symmetry and develops as a cross-over.



“*Hastatic*” order.

H. Amitsuka and T. Sakakibara, *J. Phys. Soc. Japan* **63**, 736-47 (1994).

But if the ground-state is a non-Kramer’s doublet, the Kondo effect occurs via an *excited Kramer’s doublet*.



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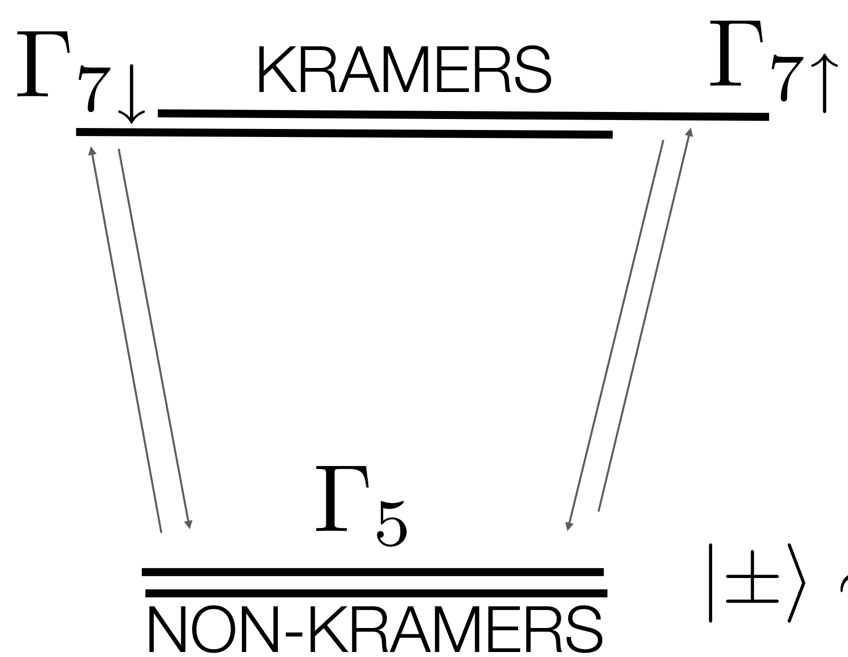

$$|\pm\rangle \sim \alpha|\mp 1\rangle + \beta|\pm 3\rangle$$

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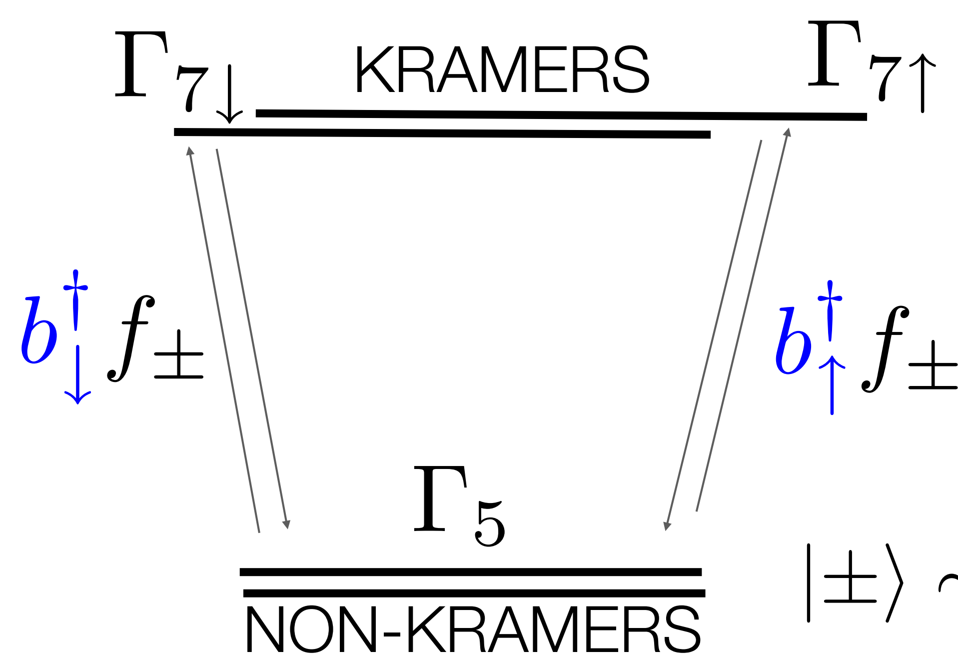

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Hybridization now carries spin and coherence necessarily breaks time-reversal symmetry.

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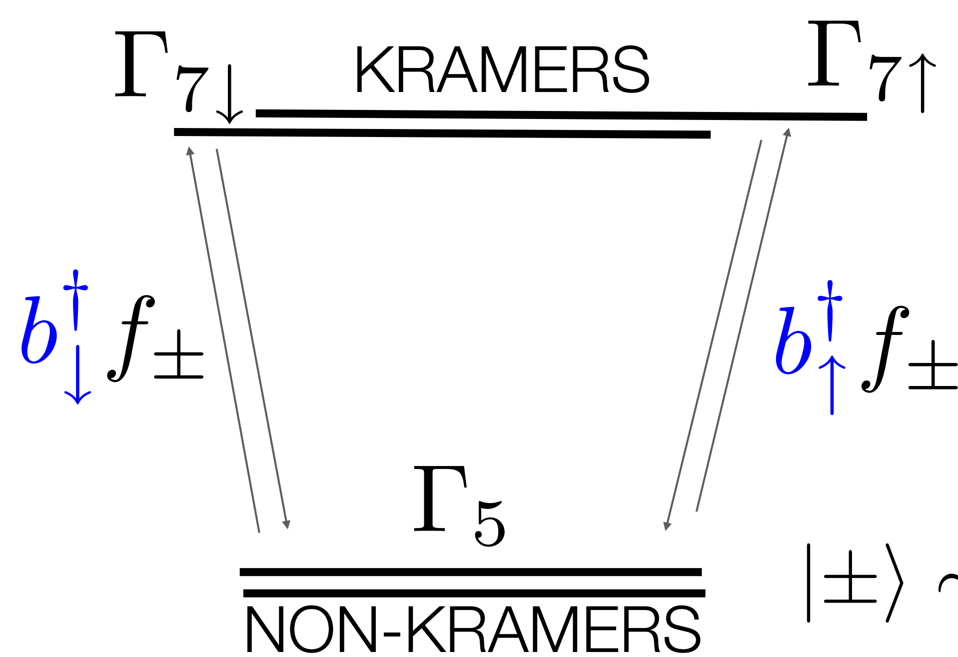

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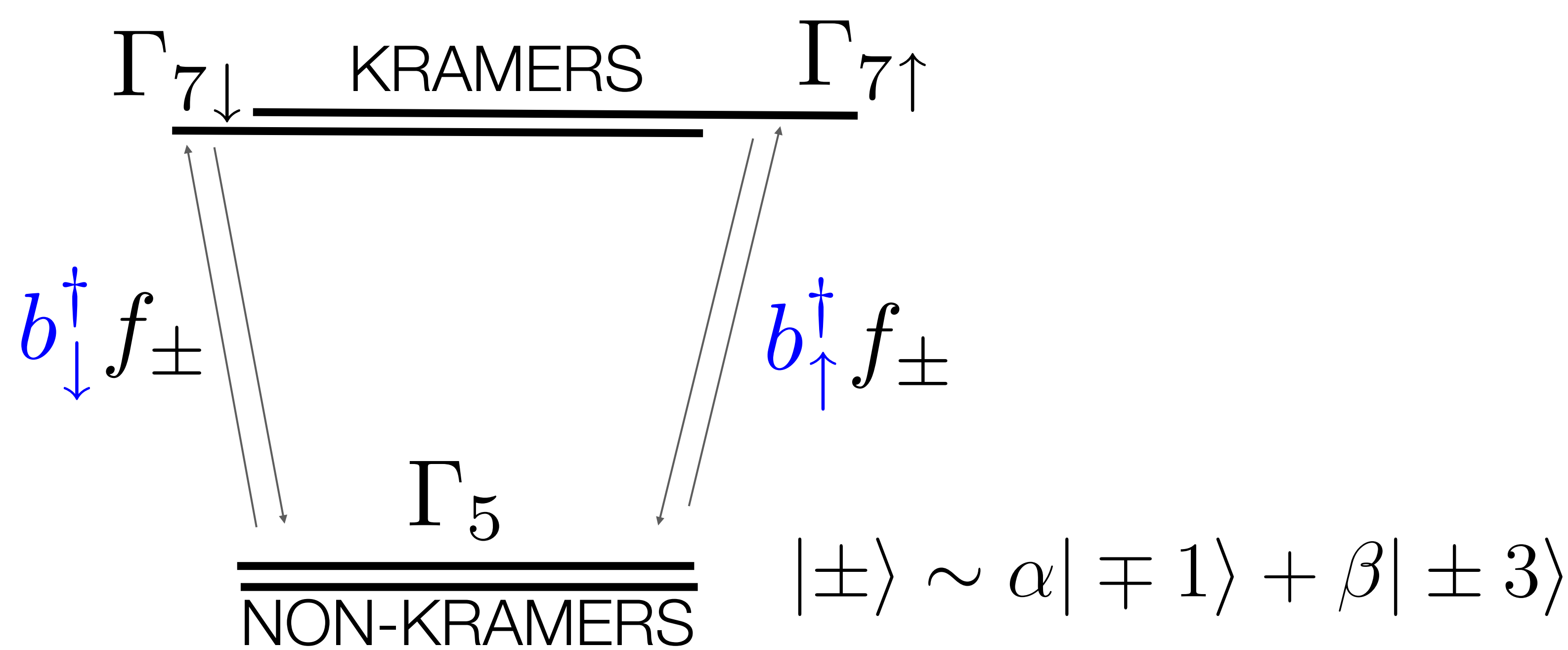

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Quasi-particles acquire the Ising anisotropy of the NK doublet

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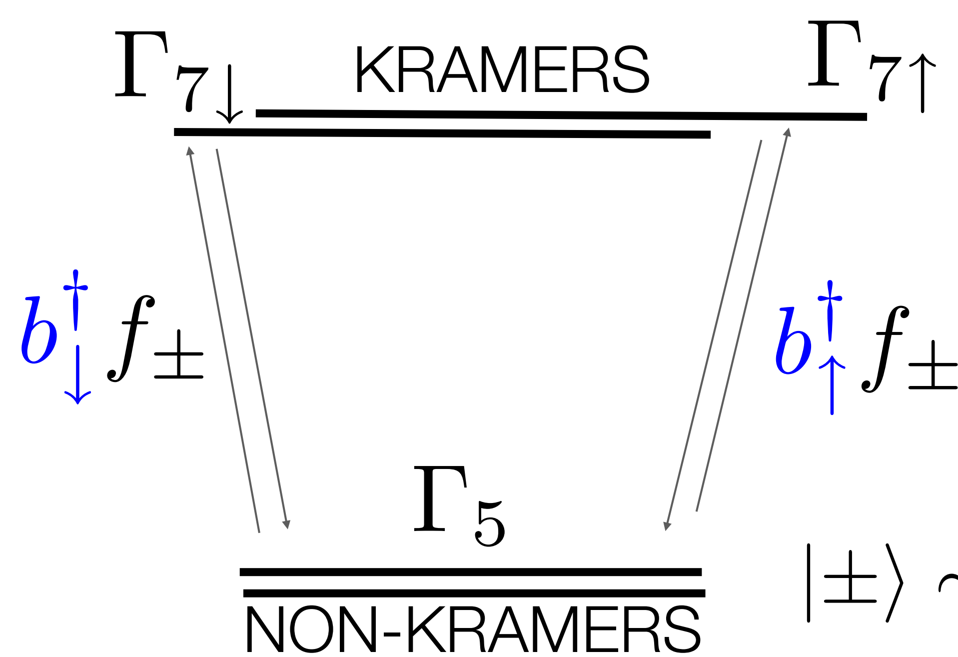

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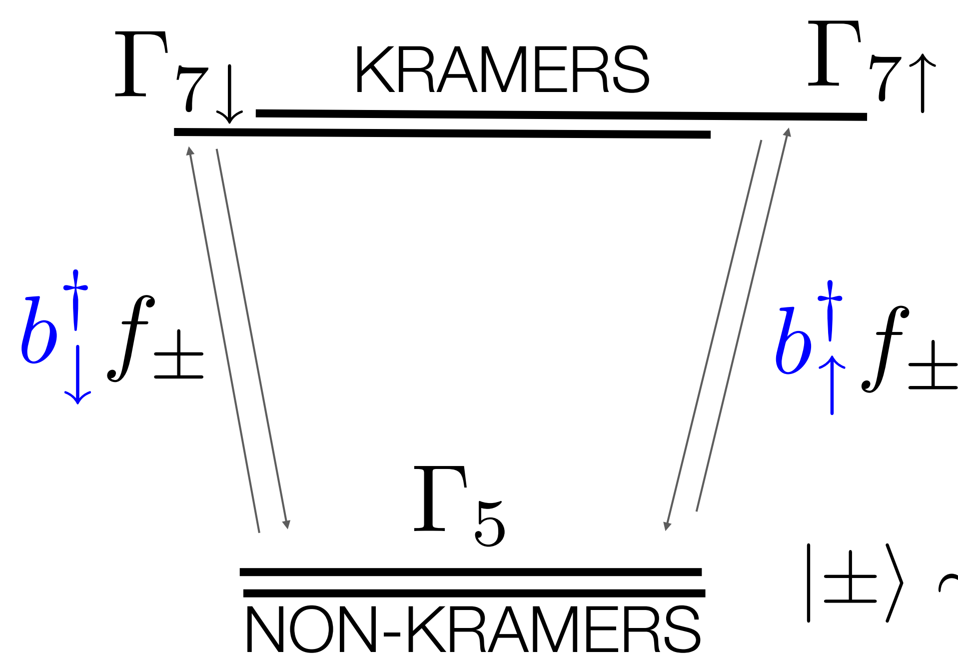

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Ising M~ O(1)

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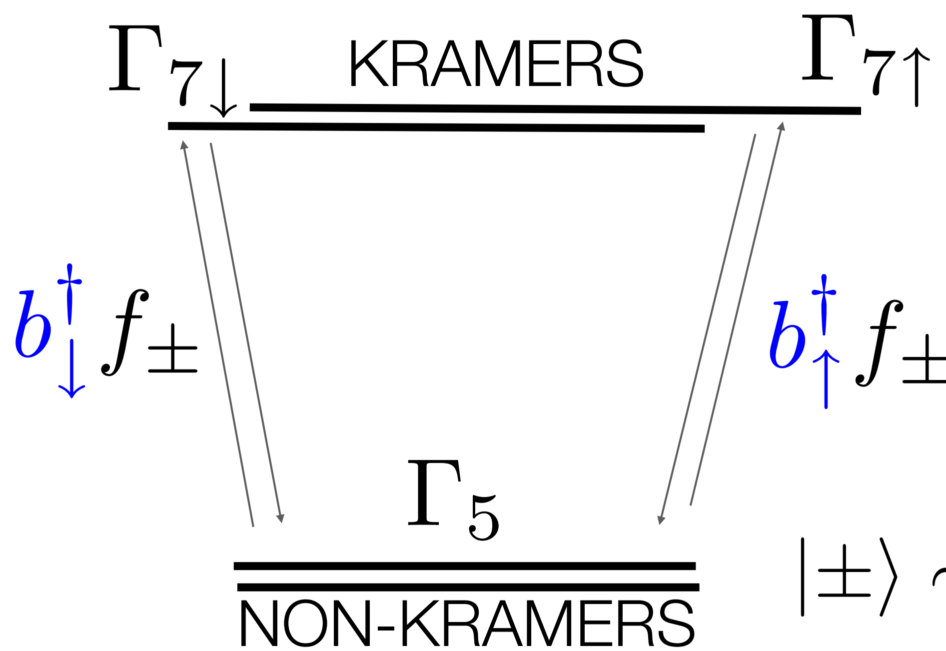

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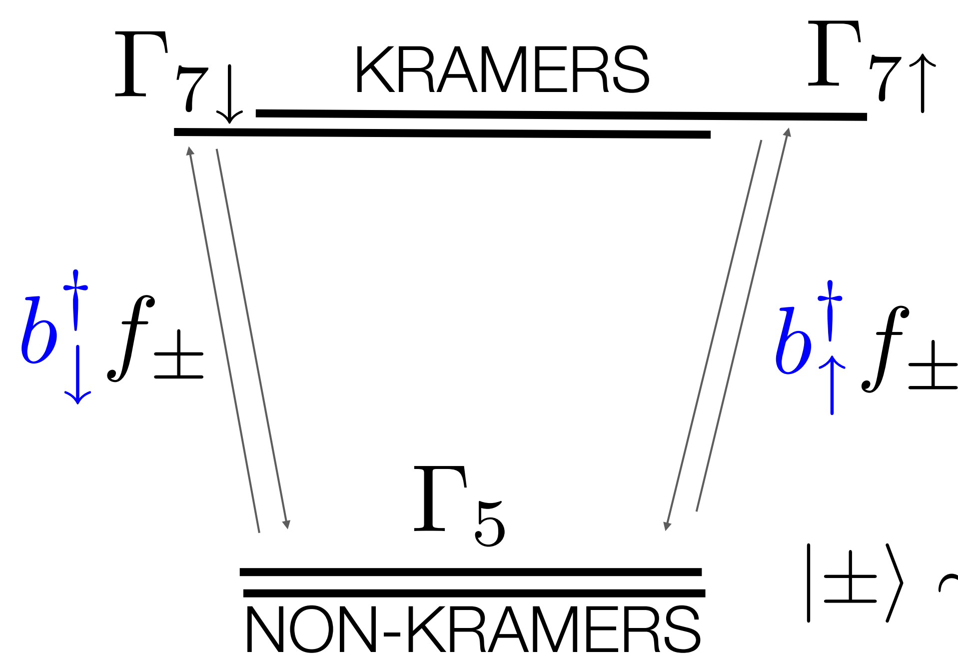

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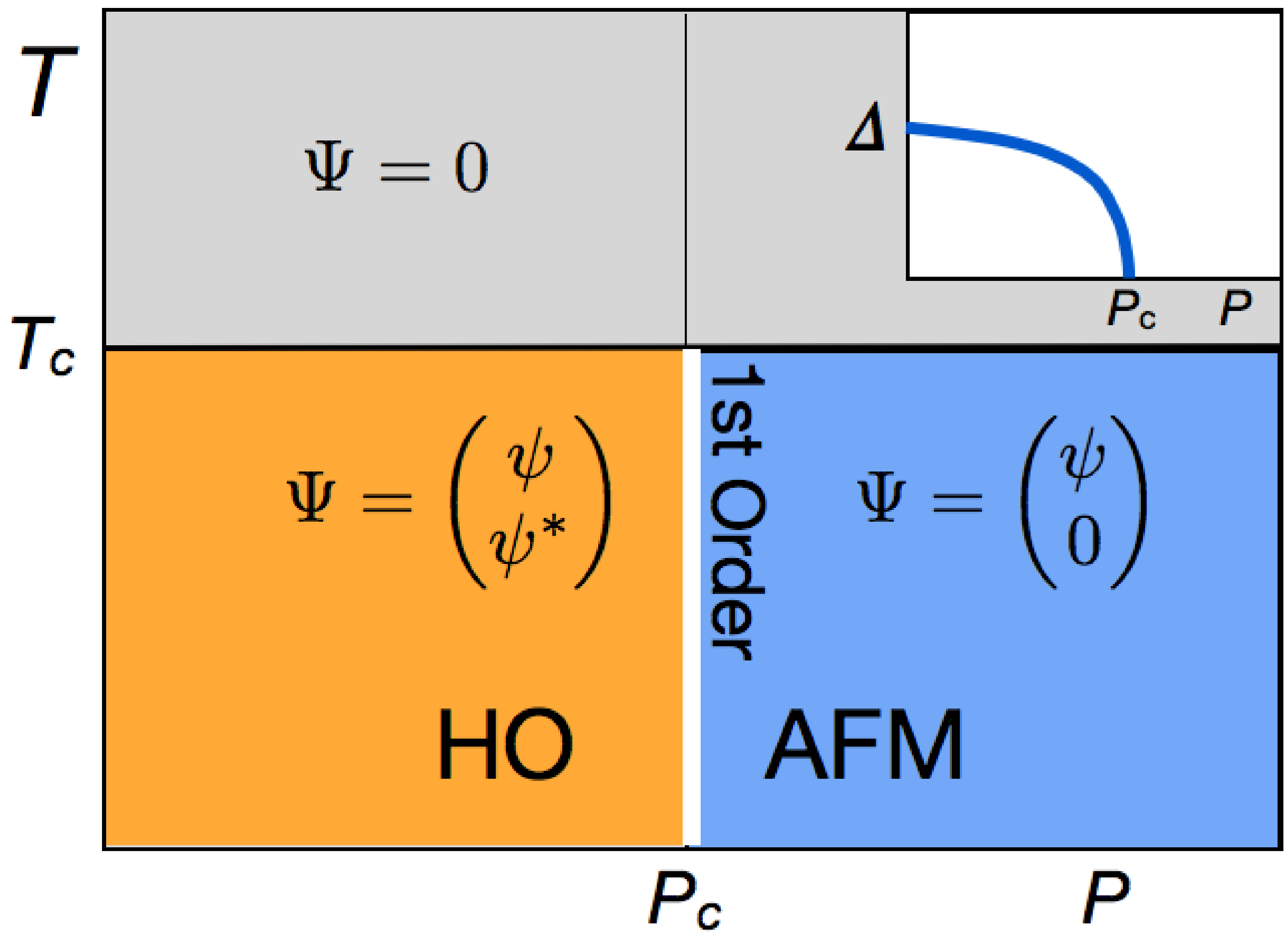
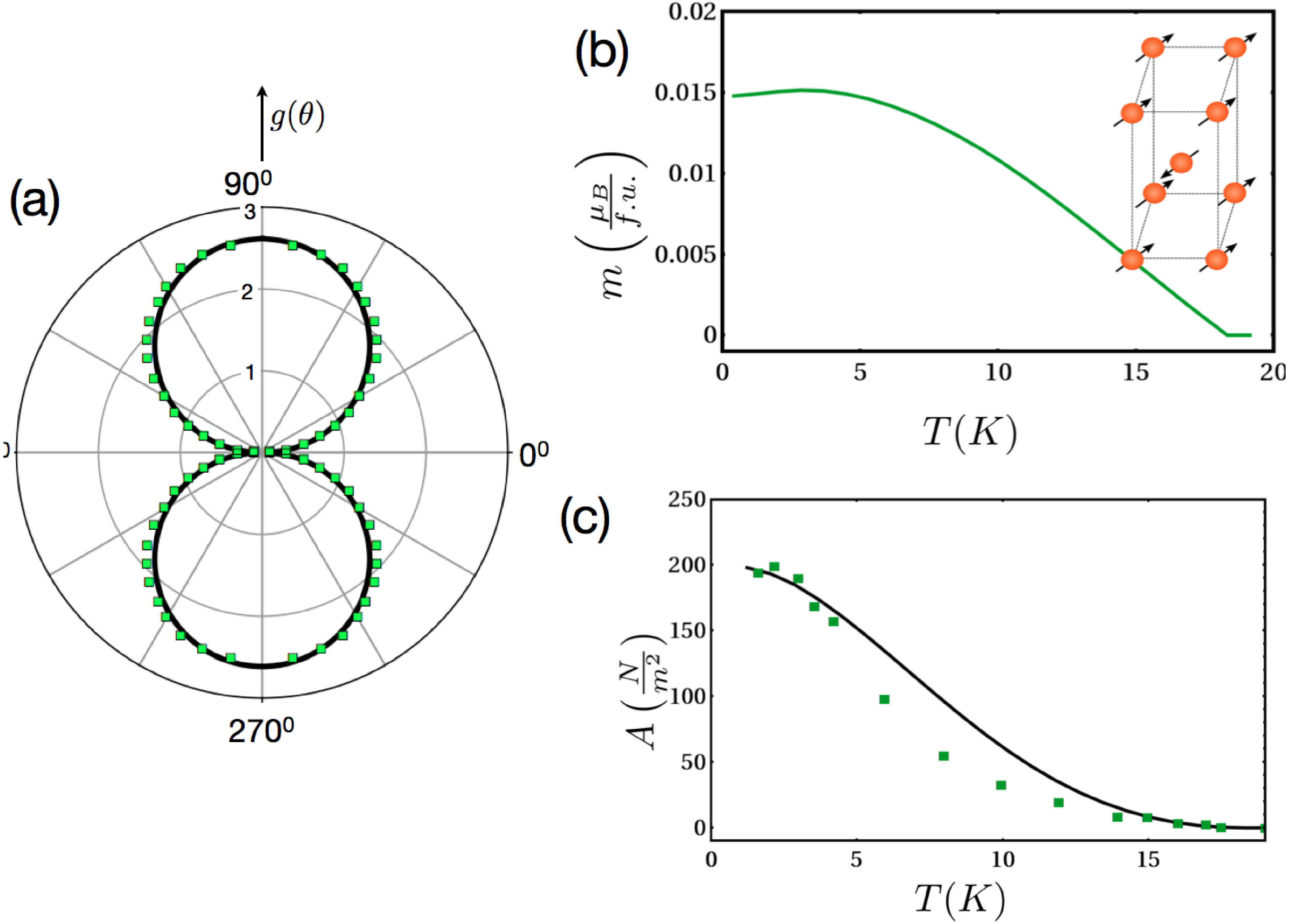


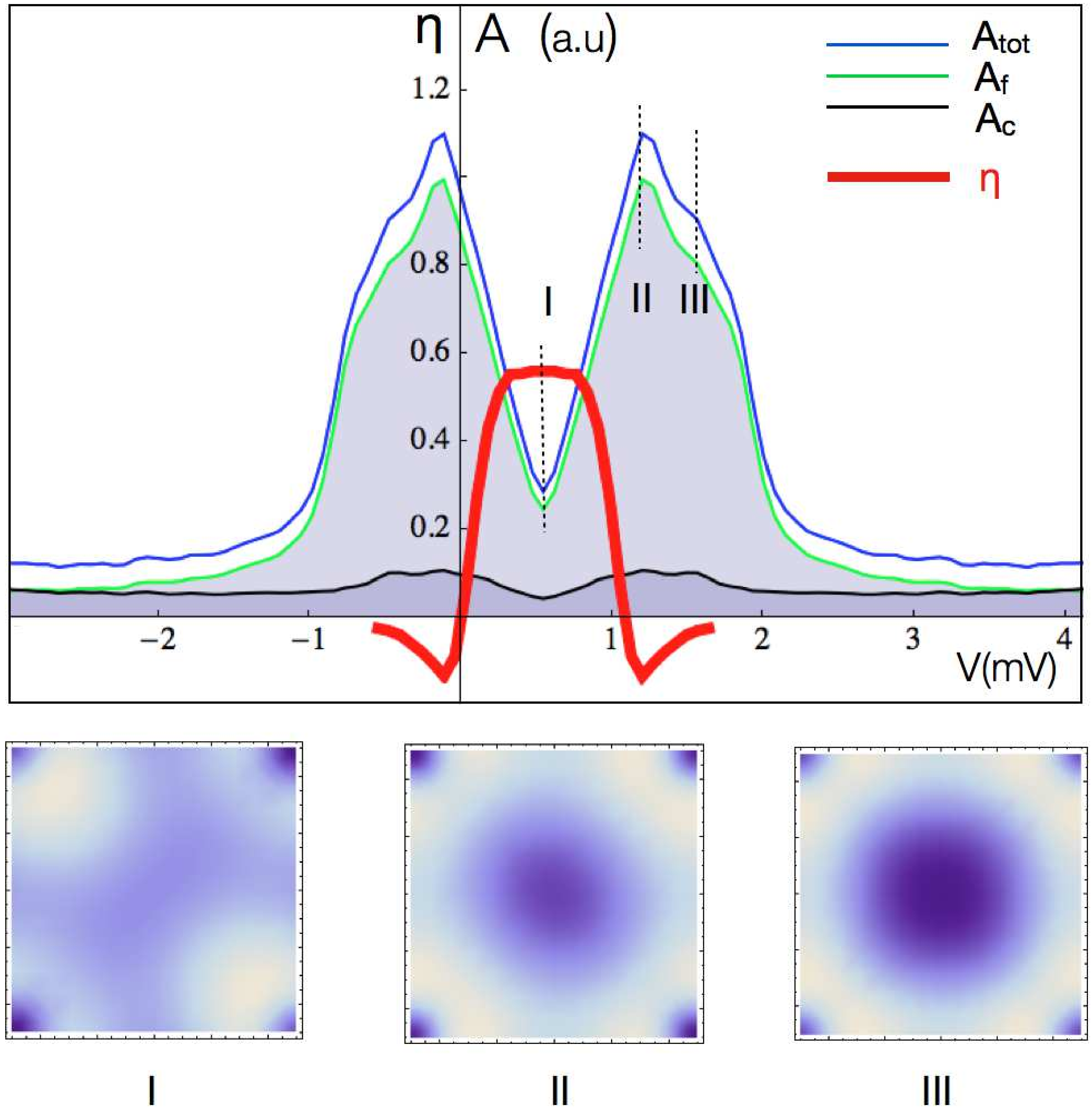
$$f[T,P] = \alpha(T_c - T)|\Psi|^2 + \beta|\Psi|^4 - \gamma(\Psi^\dagger \sigma_z \Psi)^2$$

$$\gamma = \eta(P - P_c)$$

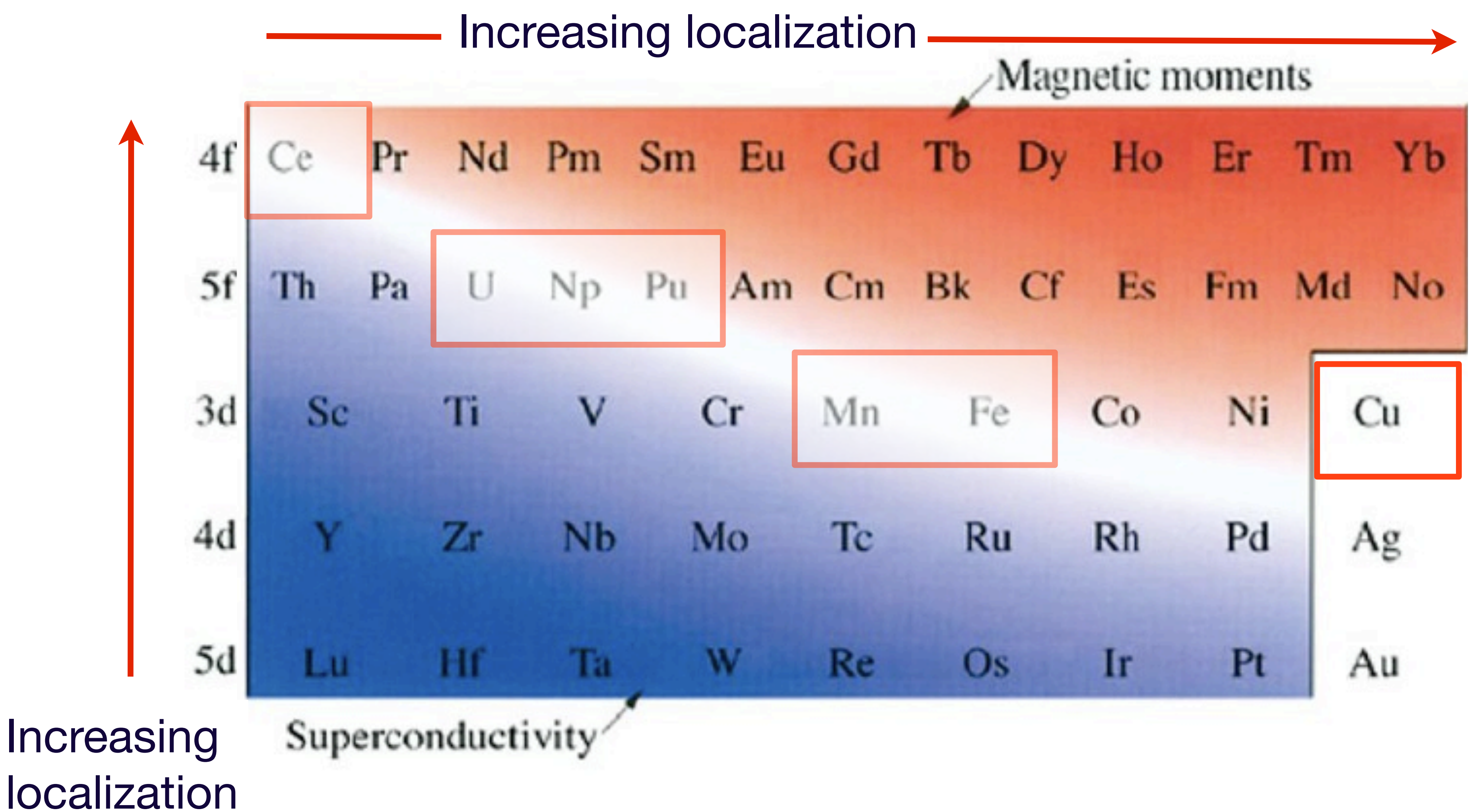
Transverse moment in conduction sea
m~ O(TK/D)



Hastatic order exhibits nematicity, accounting for anisotropic X_{xy} observed in torque magnetometry.
(Okazaki et al, Science 2011)


η
A (a.u)
1.2
0.8
0.6
0.4
0.2
−2
−1
1
2
3
4
V(mV)
I
II
III
A_tot
A_f
A_c
η
I
II
III

Conclusions.



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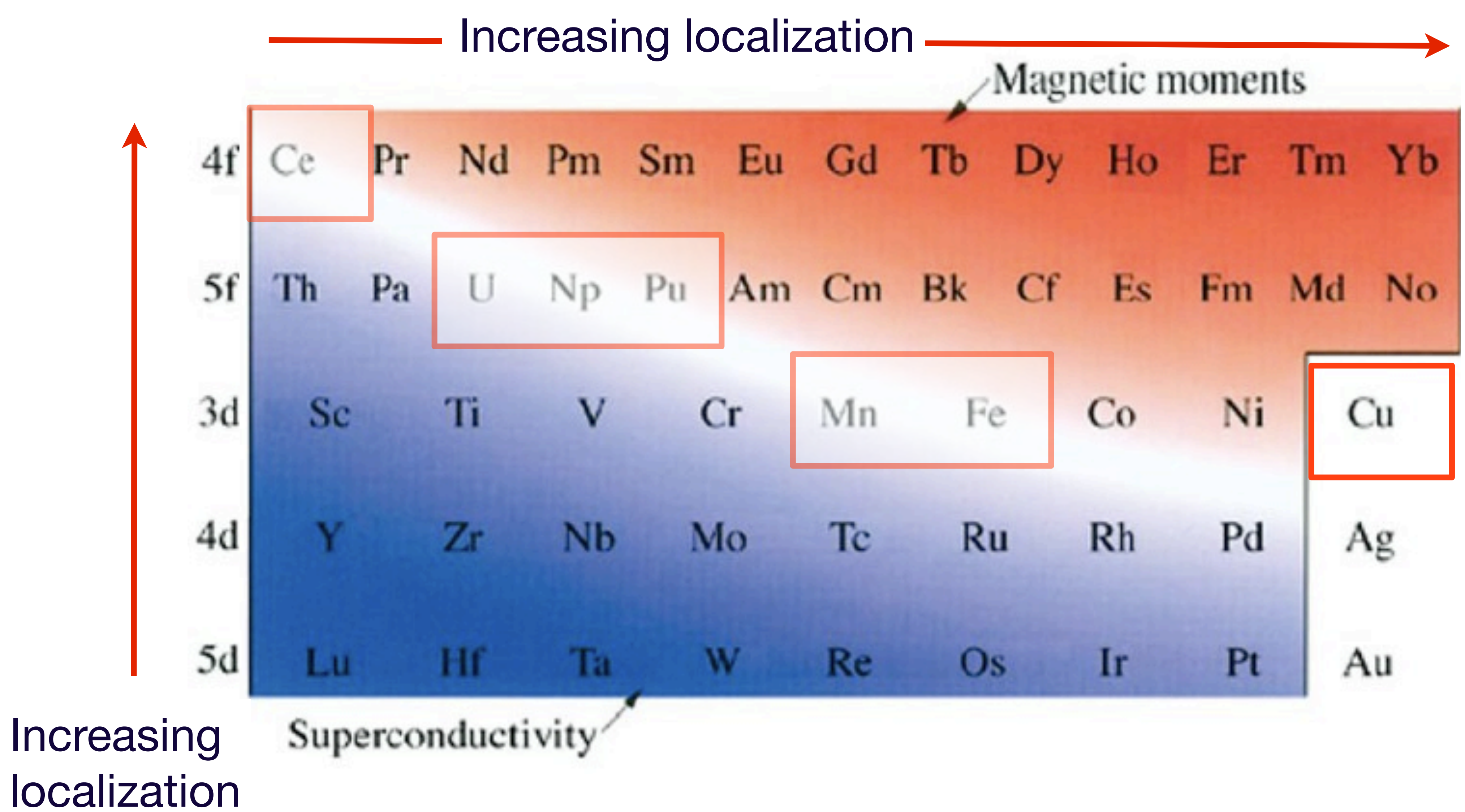
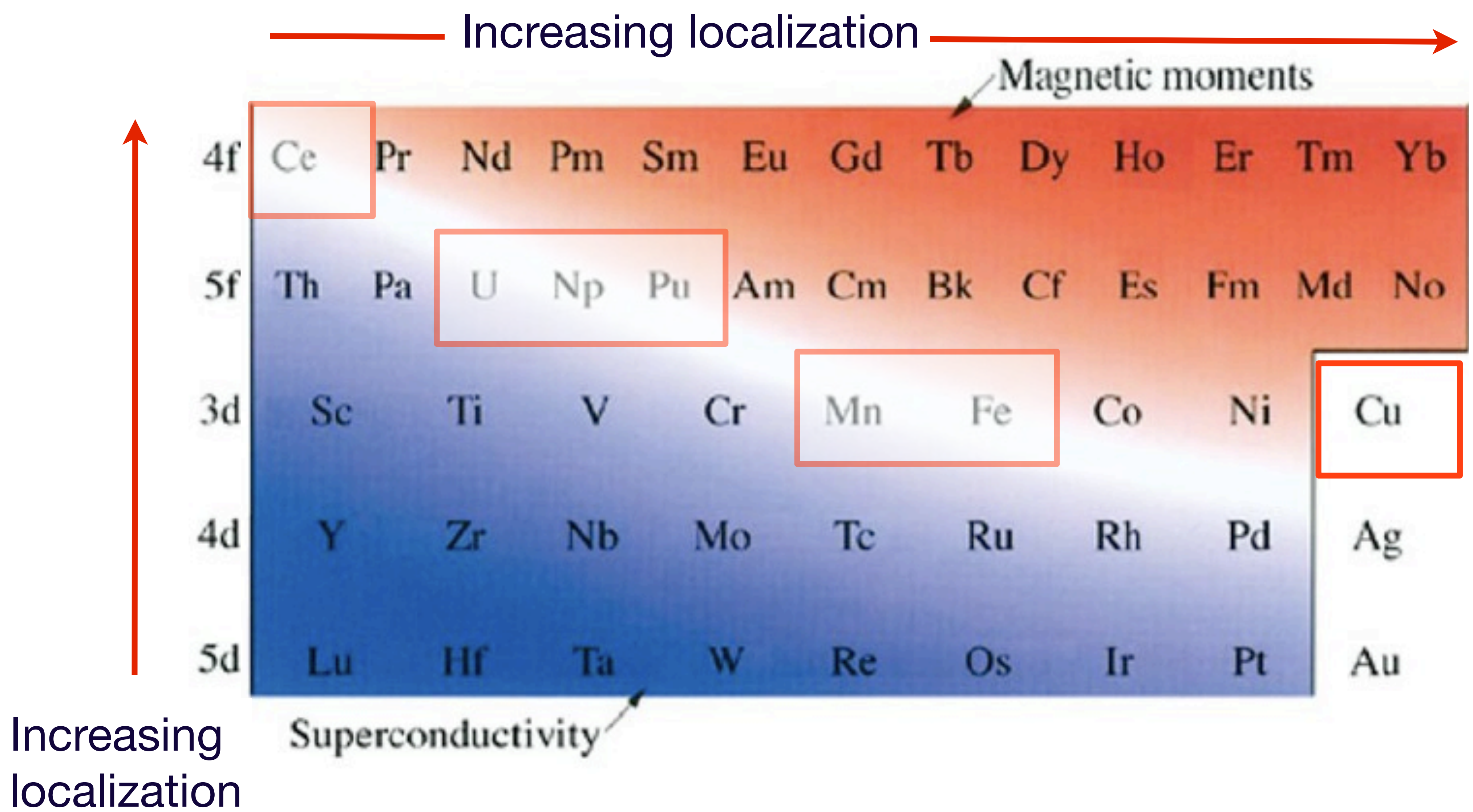


Heavy electron systems: “Penjing” (盆景) (Bonzai/miniature) high Tc superconductors;

provide key examples of many novel types of correlated electron behavior expected to develop at higher energies in d-electron systems. Tremendous advantages for research; profound opportunity for discovery and new theoretical insight.

Quantum Criticality.

Conclusions.



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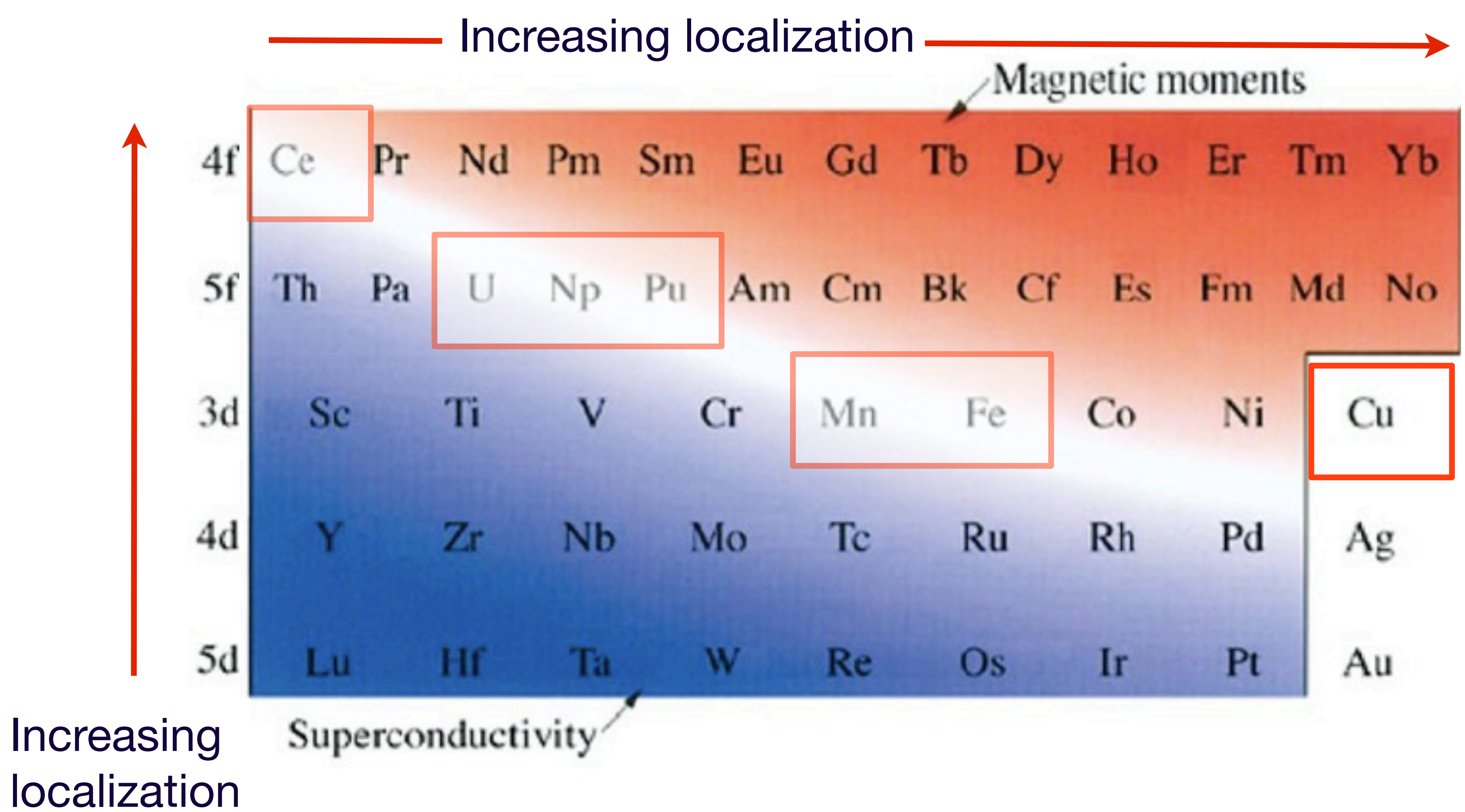
Spin structure of the heavy electron pair (possible application to pnictides?)

Conclusions.



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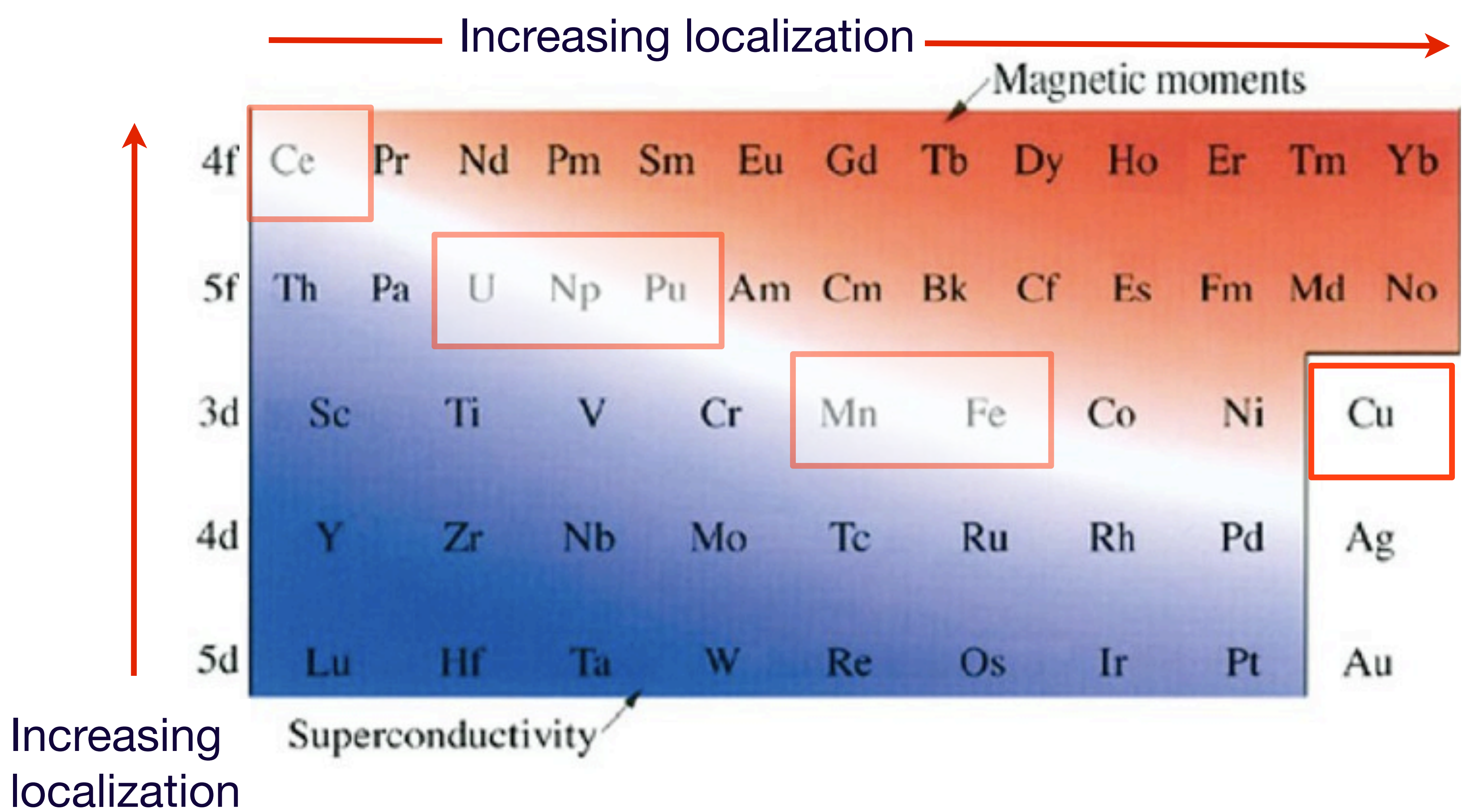

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Vortex Scenario for intrinsically quantum critical YbAlB4. Topology in metals?

Thank you!